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Department of Chemical and Petroleum Engineering

PHYSICAL AND ELECTRICAL CHARACTERISTICS OF PEMBINA OIL - EMULSION DRILLING FLUIDS

by

AMAN ULLAH LOAN, April 17, 1956

Edmonton, Alberta, Canada.

THESIS
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PHYSICAL AND ELECTRICAL CHARACTERISTICS
of
PEMBINA OIL-EMULSION DRILLING FLUIDS

submitted by Aman Ullah Loan, B.Sc. (Civil), B.Sc. (Mechanical) Engineering, in partial fulfilment of the requirements for the degree of Master of Science in Petroleum Engineering.

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Date April 24, 1956

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#10

THE UNIVERSITY OF ALBERTA

PHYSICAL AND ELECTRICAL CHARACTERISTICS
OF
PEMBINA OIL-EMULSION DRILLING FLUIDS

A DISSERTATION
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

FACULTY OF ENGINEERING
DEPARTMENT OF CHEMICAL
AND
PETROLEUM ENGINEERING

by

AMAN ULLAH LOAN

EDMONTON, ALBERTA,

April 17, 1956

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LIST OF SYMBOLS AND ABBREVIATIONS

R_m - Resistivity of mud, ohm-meters.

R_{mf} - Resistivity of Mud Filtrate, ohm-meters.

R_{mc} - Resistivity of Mud Cake, ohm-meters.

$R_m 80^\circ$ - Resistivity of Mud @ 80°F, ohm-meters.

$R_m 120^\circ$ - Resistivity of Mud @ 120°F, ohm-meters.

$R_m 160^\circ$ - Resistivity of Mud @ 160°F, ohm-meters.

RmfH - Resistivity of Mud Filtrate collected at high pressure, ohm-meters.

R_mfL - Resistivity of Mud Filtrate collected at low pressure, ohm-meters.

R_mcH - Resistivity of mud cake obtained at high pressure, ohm-meters.

R_mcL - Resistivity of Mud Cake obtained at low pressure, ohm-meters.

R_{xo} - Resistivity of the flushed zone, immediately behind the mud cake, ohm-meters.

R_w - Resistivity of native interstitial water ohm-meters.

R_t - True resistivity, ohm-meters.

R_o - Resistivity of Formation 100% filled with R_w, ohm-meters.

$(R_w)_{t_1}$ - Resistivity of sodium chloride solution or mud at temperature t_1, ohm-meters.

$(R_w)_{t_2}$ - Resistivity of sodium chloride solution or mud at temperature t_2, ohm-meters.

$(R_m)_{t_1}$ - Resistivity of mud at temperature t_1, ohm-meters.

$(R_m)_{t_2}$ - Resistivity of mud at temperature t_2, ohm-meters.

R_c - Resistivity of the effluent water or the mixture, ohm-meters.

R_1 - Resistivity of the original sodium chloride solution, ohm-meters in de Witte's equation.

R_2 - Resistivity of the invading sodium chloride solution, ohm-meters in de Witte's equation.

R_f - Resistivity of the conductive solids.

X_1 - Volume fraction of the original sodium chloride solution.

X_2 - Amount of invading liquid retained in the sample as a fraction of the total pore space.

H.P. Filtrate - High pressure filtrate.

L.P. Filtrate - Low pressure filtrate.

H.P. Mud Cake - High pressure mud cake.

L.P. Mud Cake - Low pressure mud cake.

SWSCO - Schlumberger Well Surveying Corporation.
SWSCO M.C. - SWSCO mud cup.
SWSCO F.T. - SWSCO filtrate tester tube.
F - Formation resistivity factor.
Ø - Percentage of total pore space in a rock.
S_w - Native interstitial water saturation.
n - Resistivity index exponent in Archie's Equation:

$$S_w = \frac{(F \times R_w)1/n}{R_t}$$

m - Cementation factor.
Ω - M's - Ohm-meters.
Vis. - Viscosity.
Den. - Density.
Gm. - Grams.
cc. - Cubic centimeters.
Cps. - Centipoises.
F.L. - Filter loss.
Ave. - Average.
% - Percent.
MIN. MINUTES.
Hr. - Hour.
Hrs. - Hours.
P.S.I.G (psig) - Pound Per Square Inch Gauge.
P.S.I. - Pound Per Square Inch.
lbs/U.S. Gal. - Pounds Per United States Gallon.
Temp. - Temperature.
°F - Degrees Fahrenheit.
Press - Pressure.

Soc. - Socony.

M.O. - Mobil Oil.

N. Pem. - North Pembina

V.G. - Violet Grove.

H.B. - Hudson Bay.

R.Cr. - Ross Creek.

B.C. - Buck Creek.

D.V. - Drayton Valley.

Stan. - Stanolind.

Seab. - Seaboard.

Imp. - Imperial.

Cyn. - Cynthia.

N.E. - Northeast.

Cal. Std. - California Standard.

Cit. Ser. - City Service.

t°F - Temperature in degrees Fahrenheit.

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ABSTRACT

A study of the electrical and physical properties of 25 samples of Pembina oil-emulsion drilling fluids is contained in this report. For all resistivity measurements, equipment supplied by Schlumberger Well Surveying Corporation of Canada was used. Chemical and physical characteristics of the various mud samples were obtained through the use of conventional mud testing equipment. Variation of oil-emulsion mud resistivity with mud composition, temperature and pressure were investigated. The electrical and physical properties of mud filtrates and filter cakes obtained at two different pressures and temperatures were also studied.

The results indicate that oil-emulsion drilling fluids with high oil-content usually have low resistivities owing to their high emulsifier content.

A temperature increase of 80°F to 160°F reduces the resistivity of the mud to about 50% of that at 80°F. For temperature corrections, adjusted form $\frac{(R_m)_{t_2}}{(R_m)_{t_1}} = \frac{t_1}{t_2}$ rather than Arps' original approximation formula $\frac{(R_w)_{t_2}}{(R_w)_{t_1}} = \frac{t_1 + 7}{t_2 + 7}$ gives values closer to the experimental

values of oil-emulsion mud or filtrate resistivities at temperatures up to 160°F. For temperatures above 160°F, the adjusted form $\frac{(R_m)_{t_2}}{(R_m)_{t_1}} = \frac{t_1 + 2}{t_2 + 2}$ is likely to give better results.

Both filtration pressure and filtration temperature seem to control the chemical, electrical and physical characteristics of mud filtrates. For instance, a high-pressure filtrate has a higher resistivity, a lower pH value, a lower solids concentration and is lighter in color than a low-pressure filtrate collected from the same mud. Also, filtration rate is increased by increasing the filtration pressure or filtration temperature.

For more reliable resistivities of oil-emulsion mud filtrates and filter cakes, it is suggested that these should be taken on the actual mud sample at a temperature and pressure at which filtration probably takes place in the bore hole. In the absence of temperature-resistivity data on the actual mud sample, the surface measurements should preferably be corrected to a temperature existing at the bore hole by any one of the adjusted forms of Arps' original approximation formula.

Introduction

The basic equations most often used in the quantitative interpretation of well-bore electric logs are:

$$F = \frac{R_{xo}}{R_{mf}} \qquad (1)$$

$$S_w = \sqrt[n]{\frac{FR_w}{R_t}} = \sqrt[n]{\frac{R_o}{R_t}} \qquad (2)$$

$$\text{where } n = 1.5 \longrightarrow 2.5$$

$$F = \frac{a}{(\phi)^m} = \frac{0.62}{(\phi)^{2.15}} \qquad (3)$$

The usefulness of these equations, designed to give estimates of connate water and porosity, depends directly upon the ability of the interpreter to obtain reasonably accurate values of R_t and F. The latter two variables, in turn, depend for proper estimation for their magnitude upon the resistivity of the flushed and invaded zones surrounding the well bore. The pore spaces within the flushed zone usually are assumed to be completely filled with drilling mud filtrate, while those in the invaded zone contain decreasing amounts of filtrate.

Improved logging techniques, such as "Micrologging" and "Microlaterologging" measure the resistivity of the flushed zone. These measurements depend largely on the following factors:

1. the volume of mud filtrate lost to the formation,
2. the depth of filtrate invasion,
3. the resistivity of the formation,
4. the resistivity of the mud,
5. the resistivity of the mud filtrate,
6. the resistivity of the mud cake,
7. the thickness of the mud cake.

Hence quantitative interpretation of the Microlog and Microlaterolog, to obtain estimates of R_{xo}, F and ϕ, will be most reliable when appropriate values of certain of the above factors are at hand. Experimental work has contributed greatly toward qualitative and quantitative understanding of resistivity characteristics of the flushed and invaded zones.

Shremp & Johnson[19], working with different types of drilling fluids, reported that, "filtration behavior of drilling fluid is influenced largely by the kind, concentration and particle size of solids present in the fluids. Filtration rates are influenced by the dispersion of the particles, the presence or absence of

dispersing or agglomerating chemicals." According to them, the bottom hole filter loss behavior cannot be predicted from measurements at surface temperatures in standard A.P.I. tests. Their findings show that some premium priced fluids such as oil-base or oil-emulsion muds, which in standard tests appear to have low filter losses, actually have as high or higher losses than ordinary clay-water fluids when under bottom-hole conditions. These authors suggest that, for proper comparison, filter loss tests on different types of drilling fluids should be made at temperatures and pressures approximating those under which the fluids will be used.

Later, in 1954, Ferguson & Klotz[15], investigating the chief processes by which fluid is lost to formations surrounding the well bore, reported that "dynamic filtration rates" for oil-emulsion drilling fluids are higher than for ordinary bentonite and lime-starch muds. This was shown to be true even though the A.P.I. filter-loss for the oil-emulsion mud was one-half that of ordinary bentonite and lime-starch muds.

The experimental results thus far referred to suggest that the volume of water filtrate lost to porous formations from oil-emulsion drilling fluid during drilling may be higher than is commonly thought. This should be recognized in connection with log interpretation.

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The experimental results thus far referred to suggest that the volume of water filtrate lost to porous formations from oil-emulsion drilling fluid during drilling may be higher than is commonly thought. This should be recognized in connection with log interpretation.

In practice resistivities of mud filtrates and mud cakes are often estimated from plots of experimental data obtained previously from samples of other field muds. If the resistivity of a mud is known, its filtrate and filter cake resistivities can be obtained at any temperature directly from the plots.

Recently emphasis has been placed on a more accurate method for determination of the resistivities of mud filtrate and filter cake from a particular mud. A filtration run is made in the laboratory and the appropriate resistivity measurements are made. The measurements, at room temperature, are then converted to the temperature existing at the bottom of the bore-hole. This conversion is done with the assistance of a plot of temperature-resistivity data on sodium chloride solutions of varying solid concentrations, or by Arps'[2] approximation formula:

$$\frac{(R_w)_{t_2}}{(R_w)_{t_1}} = \frac{t_1 + 7}{t_2 + 7} \qquad (4)$$

Arps' formula was developed through a data-correlation study of the effect of temperature on the electrical resistivity of sodium chloride solutions.

de Witte[3], in his discussion of a theory on current conduction through porous rocks presented the following equation:

$$\frac{1}{R_c} = \frac{X_1}{R_1} + \frac{X_2}{R_2} \qquad (5)$$

The equation was applied in his work on core samples. They were first saturated with a sodium chloride solution of certain solid concentration and then flushed with a similar solution of another concentration. The effluent water was a mixture of the original sodium chloride solution and the flushing solution.

Equation (5) when applied to a mixture of conductive solids and water, such as drilling fluids, becomes:

$$\frac{1}{R_c} = \frac{1 - X_w}{R_f} + \frac{X_w}{R_w} \qquad (6)$$

where X_f and X_w are volume fractions of the conductive solids and the water, respectively.

de Witte[4] finds it reasonable to assume that the combination of randomly distributed conductive particles and water found in a dirty sandstone would behave electrically in a similar way to a slurry made up of the same amount of conductive solids and water. The resistivity of the rock which contains this "slurry" is then F times the resistivity of the slurry.

This pattern of thought may be extended to the prediction of resistivity changes of oil-emulsion mud as the oil content and liquid phase resistivity are varied.

The oil and non-conducting solids may be thought of as the matrix of a porous rock, while the intimate mixture of conducting solids and water may be thought of as the slurry or saturating liquid phase. It is not the purpose of this thesis to investigate the quantitative validity of the equation based on the above concept. However, the concept is presented since it is of assistance in seeking reasons for trends indicated by data presented herein.

Sherborne & Newton[21] investigated the electrical characteristics of actual field samples of five to ten commonly used water-base muds. Since their work is directly related to the work reported here, Sherborne & Newton's conclusions are outlined:

1. The effect of raising the mud temperature from 100°F to 180°F is to decrease the resistivity of the mud or its filtrate by about 50 per cent.
2. The resistivity of the mud, in most cases, approximates that of its filtrate, R_{mf}.
3. The change in R_m caused by the addition of chemical is not the same function of the amounts of chemical added to each mud.
4. The effect produced by increased sodium chloride is to reduce markedly R_m and R_{mf}.

5. Weighting materials, such as Baroid and limestone tend to increase R_m.
6. Cement and counteracting reagents reduce R_m.

The experimental work reported herein also was done on field samples of drilling fluids. The electrical and physical characteristics of 25 samples of Pembina oil-emulsion drilling fluid were investigated.

Specifically, the aims of the experimental program were to measure and investigate:

1. the resistivities of the field samples of drilling fluids, their filtrates and their filter cakes,
2. the effect of temperature on the resistivities of these samples,
3. the effect of pressure on the resistivities of these samples,
4. the effect of filtration pressure, if any, on the chemical electrical or physical properties of the mud filtrates or filter cakes,
5. the effect of sodium chloride and commercial emulsifiers on R_m, R_{mf} and R_{mc},
6. the effect of pressure and temperature on the static filtration rates of these muds.
7. the accuracy of the common assumption that oil-emulsion fluids, their filtrates and filter cakes have resistivities quite similar to those for conventional water-clay base muds.

DESCRIPTION OF THE EQUIPMENT

High-Pressure Filter Press

Two identical Baroid high-pressure filter presses were used to collect filtrates and filter cakes from each mud sample at two different pressures and temperatures. The filter press employed for high-pressure filtration had a water-bath which surrounded the filter cell. A variac was connected to the heating element of the water-bath. Any temperature between 110°F to 180°F could be obtained by adjustment of the variac. The two filter cells are shown connected to their sources of pressure-supply in Plate I. Figs. 1 and 2 show the assembly details of the filter cells.

Fann Mud Still

This still (Plate III) is a distillation apparatus for the composition analysis of oil-emulsion muds. Both water and oil distil out of the 100 ml. mud sample into a graduated cylinder. Volumetric percentages of water and oil can be read. The apparatus was calibrated with laboratory samples of oil-emulsion muds of known compositions.

Beckman pH Meter

All pH values for muds and their filtrates were obtained on a conventional Beckman pH meter shown in Plate I. The recommended operational procedure was followed closely for all measurements.

Fann Viscosimeter Model 31

Viscosities of muds, and initial and 10-minute gel strengths were obtained on the laboratory model of the Fann viscosimeter shown in Plate I. The meter was calibrated with a series of oils of known viscosity. Fig. A-1 shows the calibration curve for the instrument.

Resistivity Measuring Equipment

Resistivities of mud filtrates and mud cake were obtained on the Schlumberger Well Surveying Corporation equipment loaned to the University of Alberta.

The SWSCO mud cup and electronic "tester box" (Plate II) were used to obtain R_m for each mud sample. As a check, R_m was also obtained by the SWSCO filtrate tester tube (Plate IV). Fig. 3 shows the assembly details of the SWSCO filtrate tester tube.

R_{mc} values were obtained on the SWSCO mud cake

tester (Plate IV). The mud cakes were collected in mud cake holders as shown in Fig. 4. Assembly details of the mud cake resistivity apparatus are shown in Figs. 4 and 5.

During the study of the effect of the temperature on the resistivity of oil-emulsion muds, a Ruska temperature bath (Plate III) was used to control the temperature of the mud sample within the SWSCO mud cup. Mud temperatures up to 160°F could be obtained easily.

To investigate the effect of high pressures on the resistivity of mud, a pressure cell was designed to surround the SWSCO mud cup. The upper pressure limit on the cell was 1000 P.S.I.G. "O-rings" were used to effect a pressure seal between the metallic parts of the casing and the mud cup electrode. Plate II shows the SWSCO mud cup in the pressure cell, which is connected to a pressure-source.

Experimental Procedure

Each mud sample was first stirred in a Waring blender for about two minutes. Its resistivity was then obtained by the SWSCO mud cup and bythe SWSCO filtrate tester tube. The temperature was recorded for each measurement.

The sample was then transferred back to the Waring blender where it was stirred again for about half a minute. An equal quantity of the sample was then put in the two cells of the Baroid filter presses. These were

subjected to different pressures (100 P.S.I.G. & 1000 P.S.I.G.). In the case of the first seven field samples, filtration runs were carried out at room temperature. To simulate bottom-hole conditions filtration temperature was increased to about 115°F during high-pressure filtration for the rest of the field samples. Thirty-minute filter losses were obtained both for high and low-pressure runs.

Viscosity, gel strengths (initial and 10-minute), composition, sand content, density, and pH measurements were made on the remaining portion of the mud sample.

Both high and low-pressure filtration runs were allowed to proceed until a minimum of seven cc. of the filtrate was obtained in each case. Resistivities and pH values of both high and low-pressure filtrates were obtained. Temperature was recorded during each resistivity measurement. The color of the two filtrates was observed.

Resistivities of the mud cakes collected at high and low-pressures were measured by the SWSCO mud cake testers. Temperatures were recorded. The cakes were examined under a microscope to note qualitatively the amount of oil entrapment and the configuration of their pore spaces.

In the case of the last ten field samples filtrates were also tested for their solids concentration. In each case, 2 cc. of filtrate was transferred to a tube of known weight and then weighed. The filtrate was then allowed to evaporate from the tube at 110°F in a thermo-

statically controlled electric furnace. When the filtrate was evaporated, the solids were dried at 180°F for about an hour. The solids remaining in the tube were then weighed and their concentration calculated in PPM. Identical conditions of temperature and pressure were maintained for the evaporation and drying of each filtrate sample. The weighings were made to 0.0001 gram.

The last 14 samples of Pembina oil-emulsion mud were used to study the effect of temperature on resistivity. Each sample was heated gradually from 80°F to 160°F in the Ruska temperature bath and mud resistivity was recorded for each 5°F rise in temperature of the mud.

For the high-pressure, high-temperature resistivity investigation the SWSCO mud cup containing the sample was placed in the pressure cell. This was put in the Ruska temperature-bath and the mud was heated gradually at atmospheric pressure. A thermometer, in the thermometer-well of the pressure cell, provided the temperature readings on the sample within the mud cup. After each five degree rise in temperature the resistivity of the mud was recorded. The pressure on the mud was then increased to 800 P.S.I.G. in stages and the resistivity was recorded for each increment of pressure.

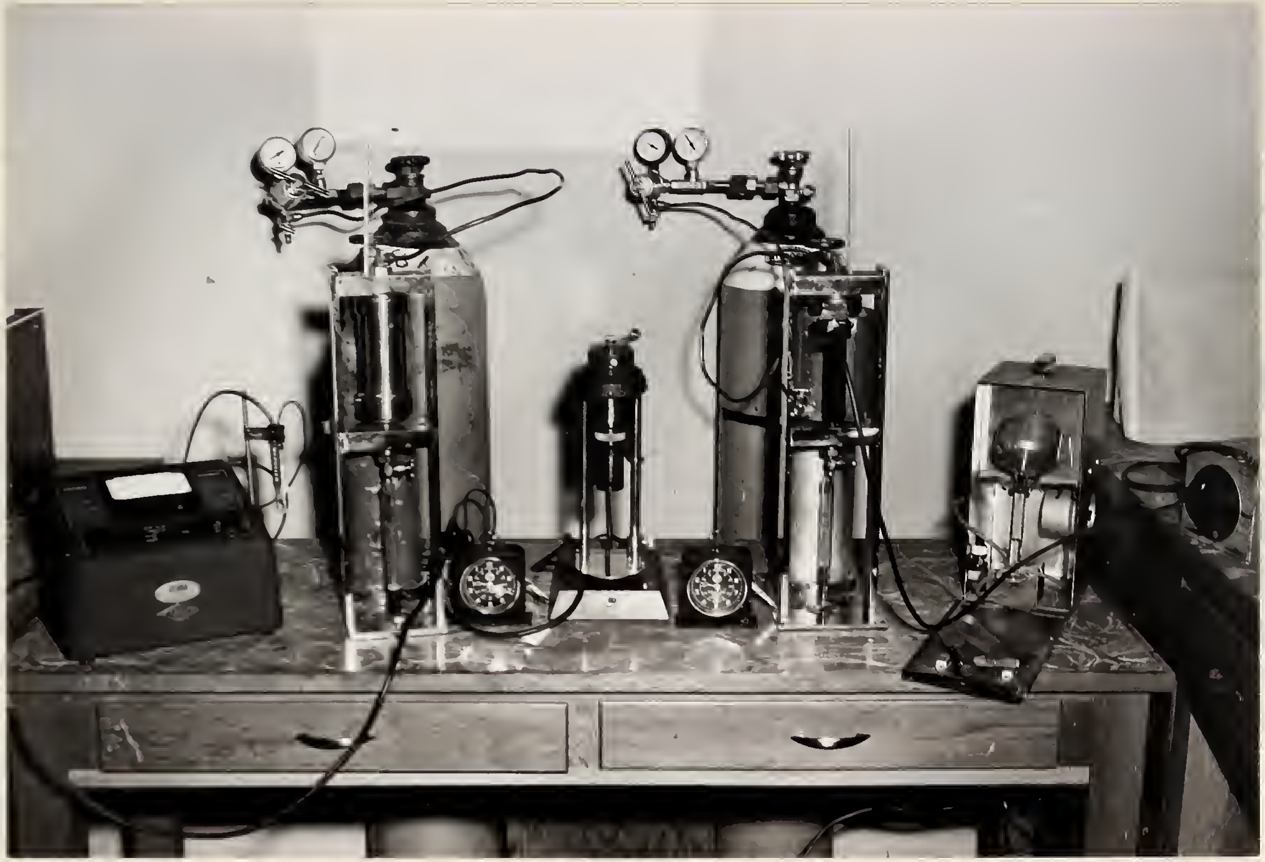

Plate I -- Overall View of the Equipment Including Left to Right, Beckman pH Meter, Baroid High-Pressure Filter Press, Baroid Time Clock, Fann Viscosimeter Model 31, Baroid High-Pressure Filter Press with Temperature Bath, Fann Mud Still, and a Variac.

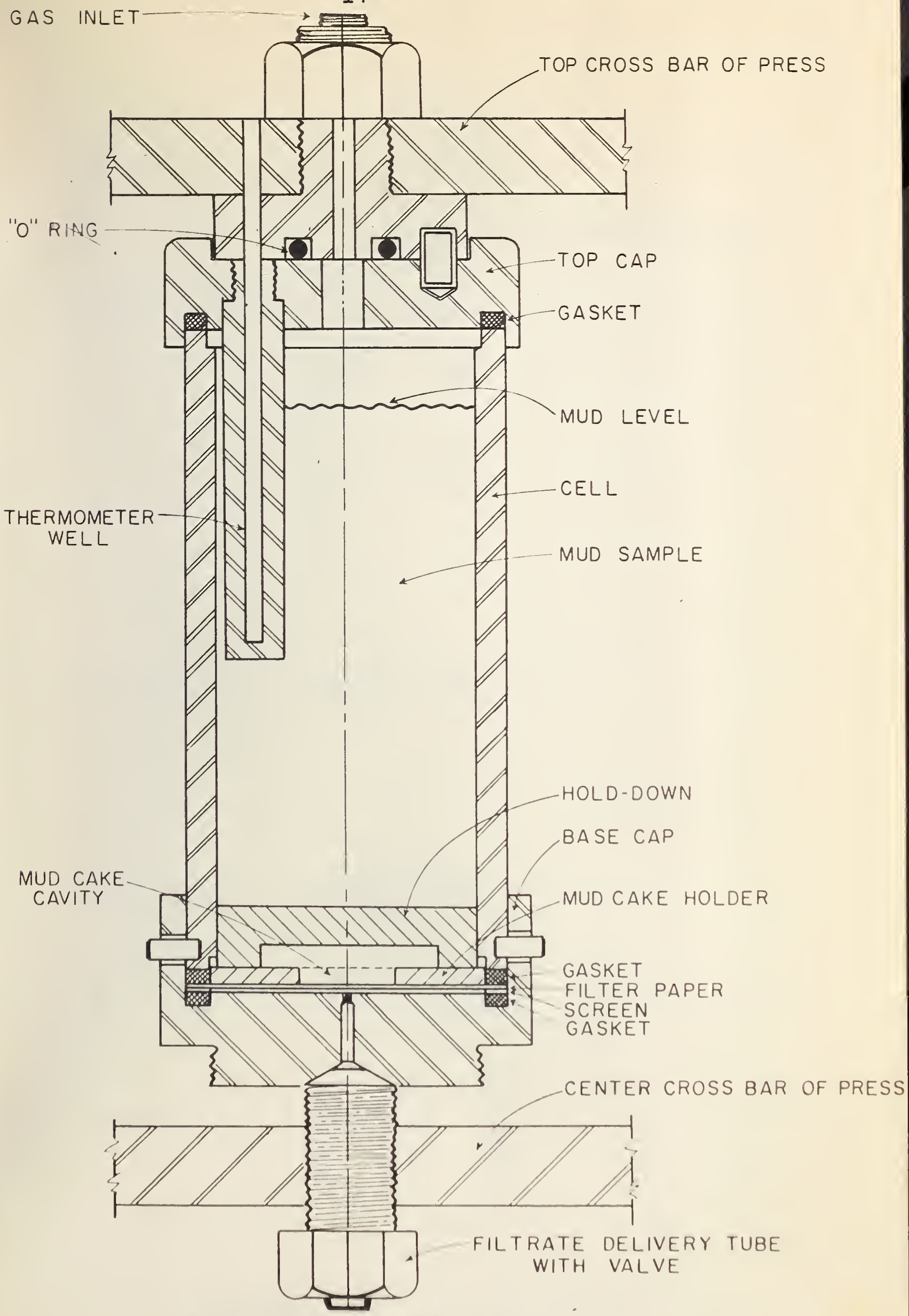

Fig. "1"   FILTER CELL

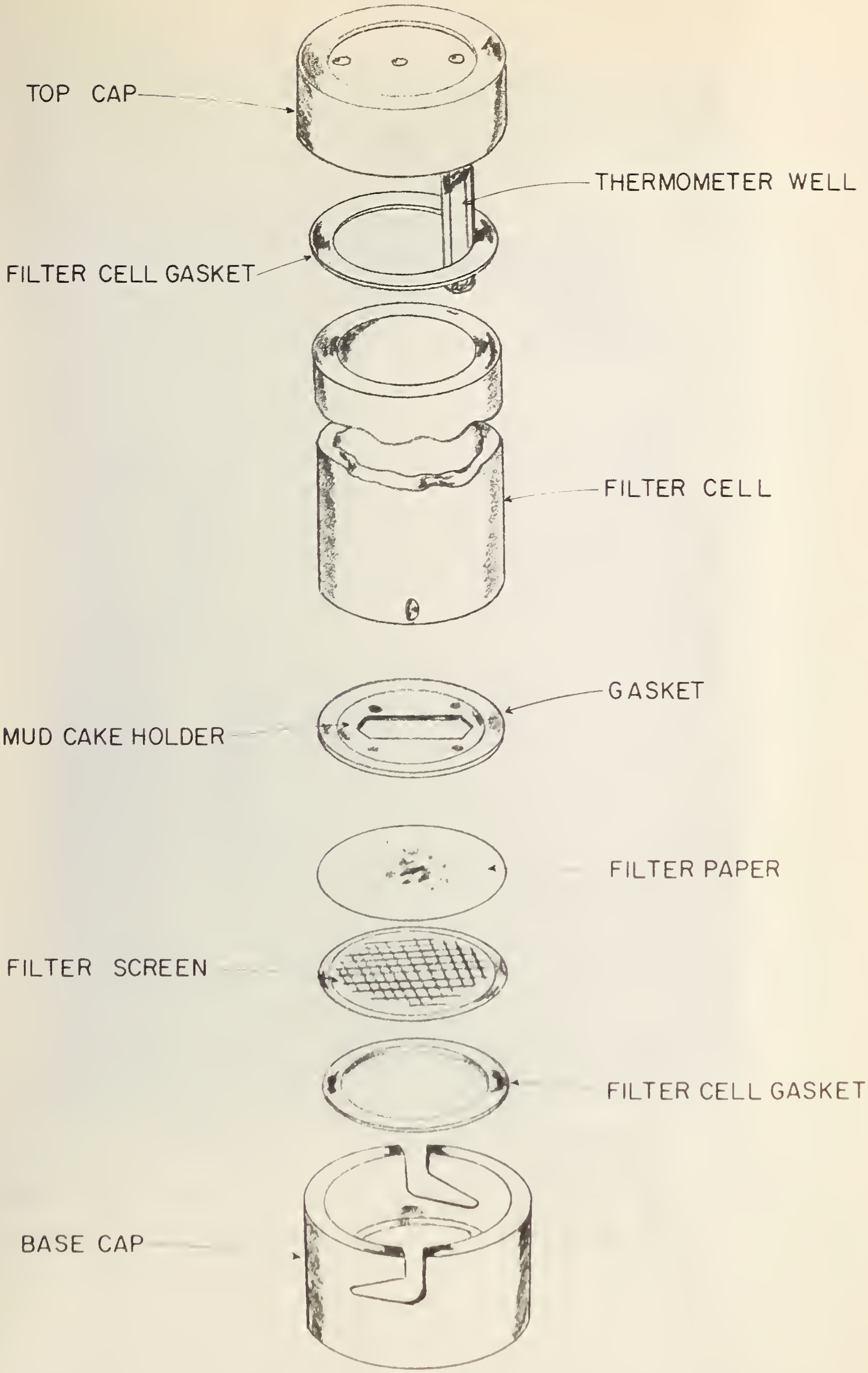

Fig. "2"

ASSEMBLY OF FILTER PRESS

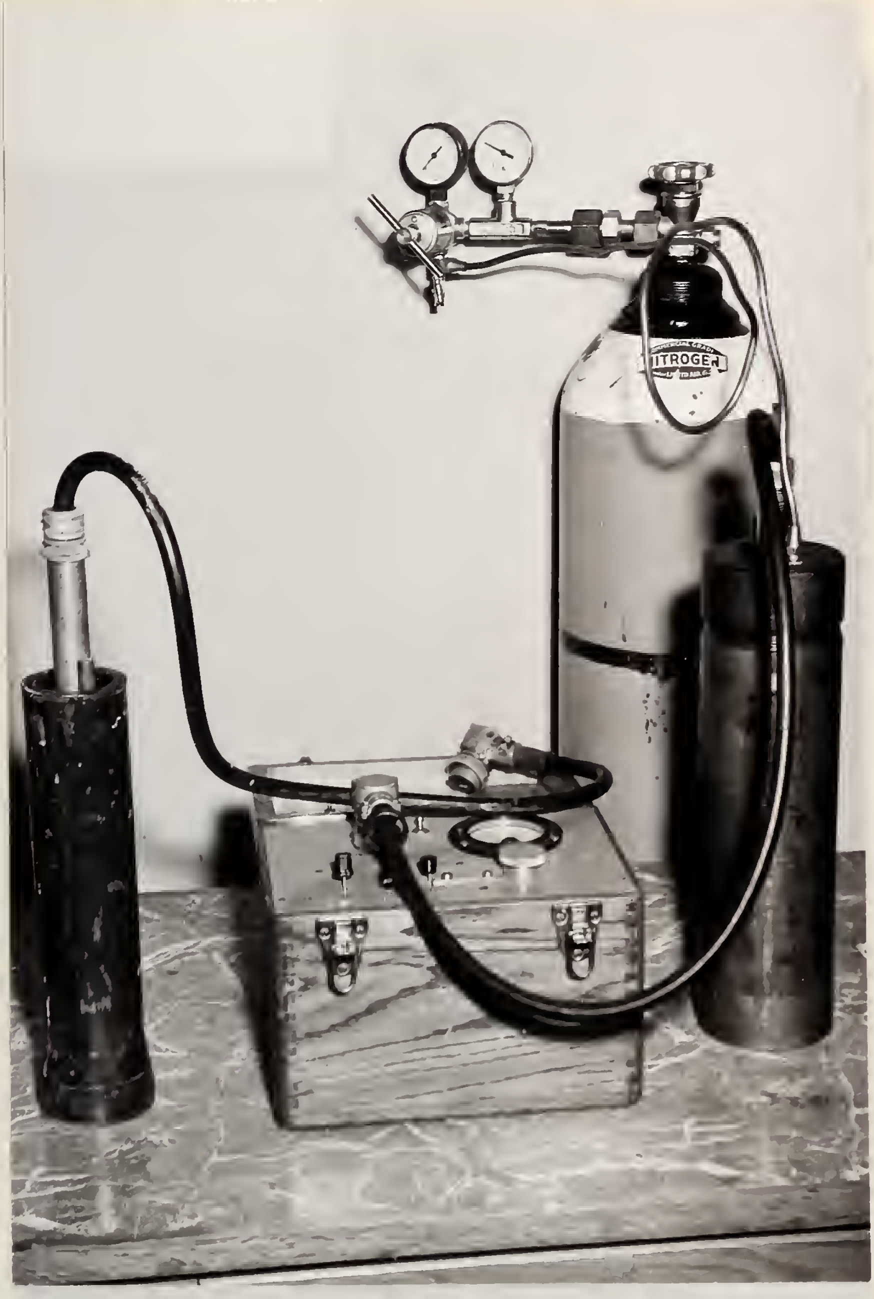

Plate II -- View of the SWSCO Mud Cup, Electronic Mud-Tester Box, the SWSCO Mud Cup in Its Pressure Cell Connected to Its Pressure Source.

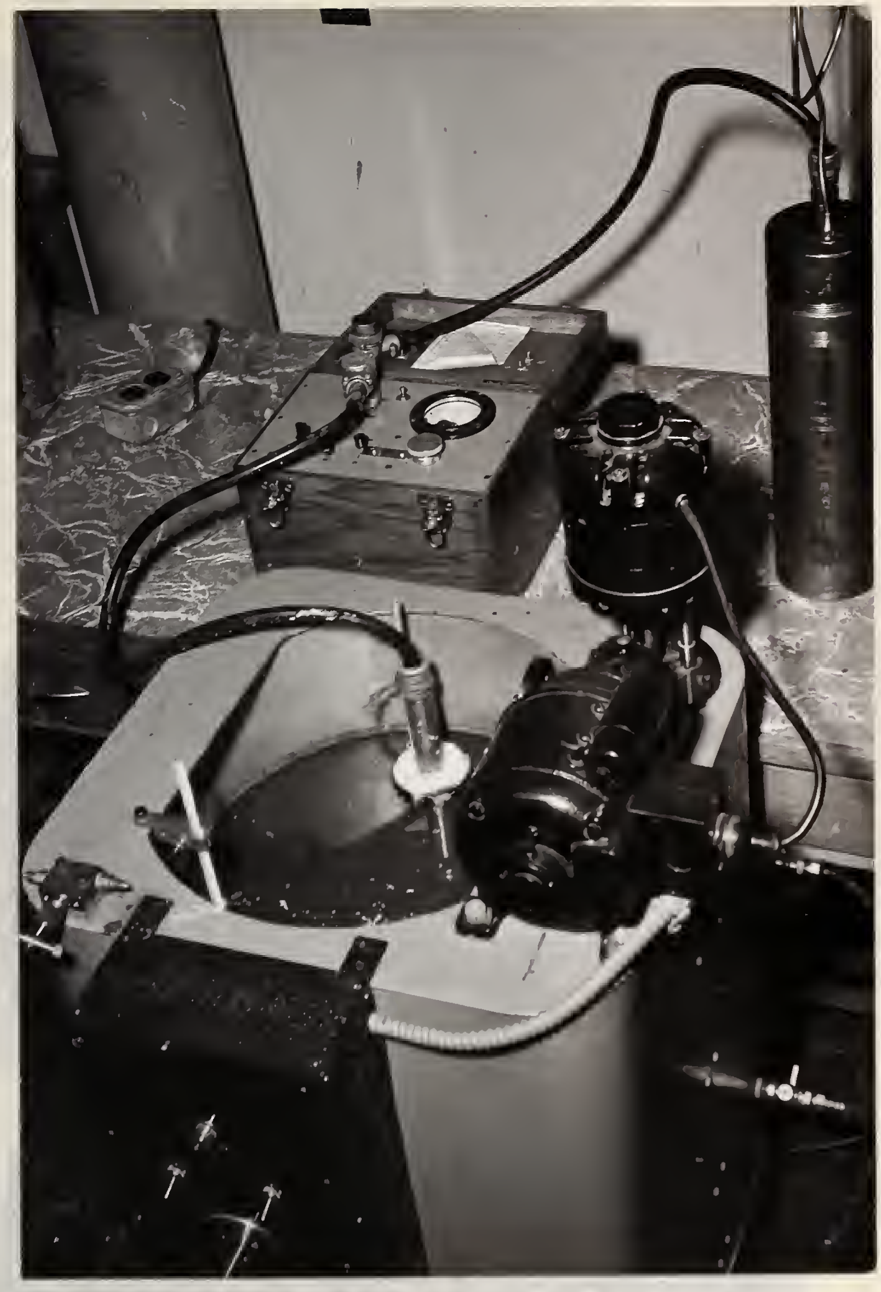

Plate III - View of the SWSCO Mud Cup in Ruska Temperature Bath.

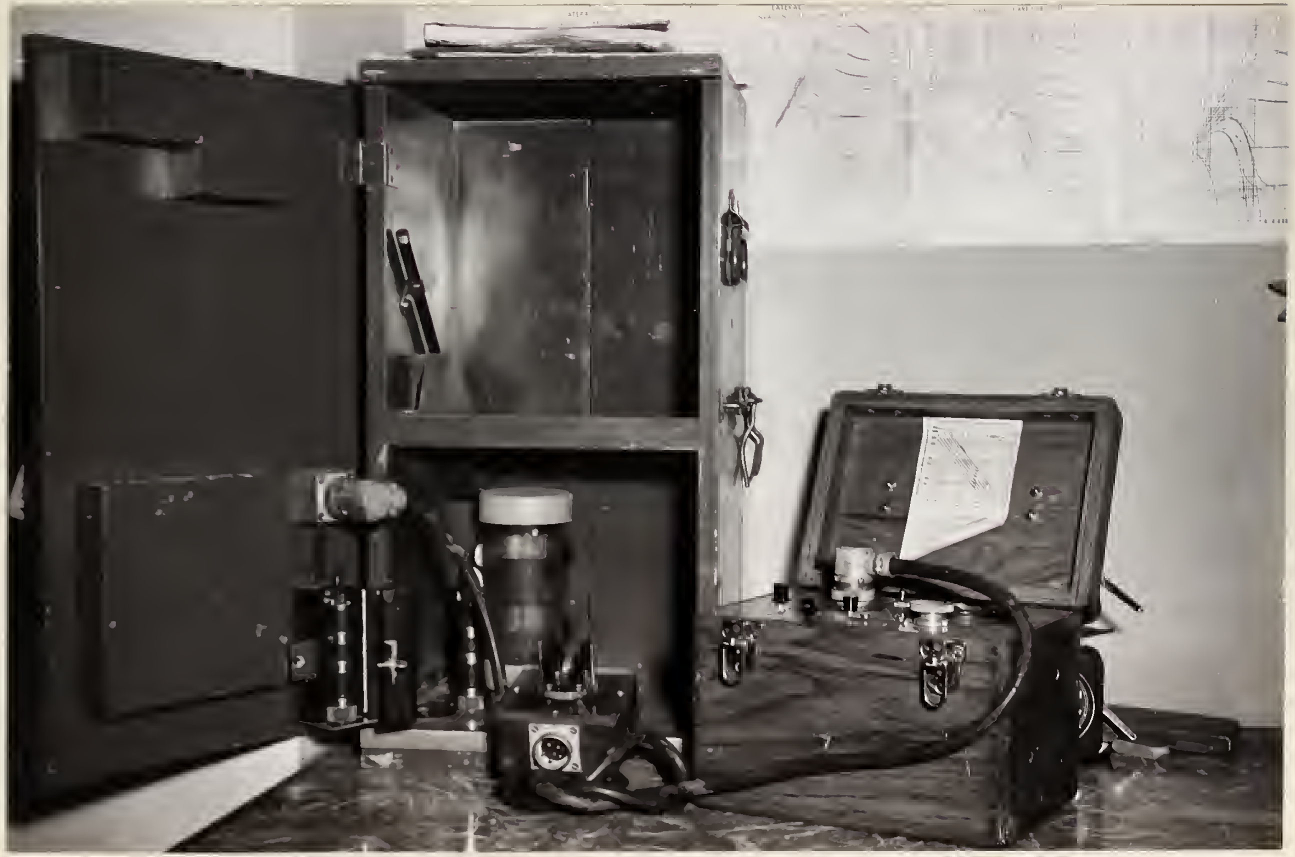

Plate IV -- The SWSCO Filtrate Tester Tube is Shown Connected to the Electronic Mud-Tester Box. In the Centre is the SWSCO Mud Cake Tester.

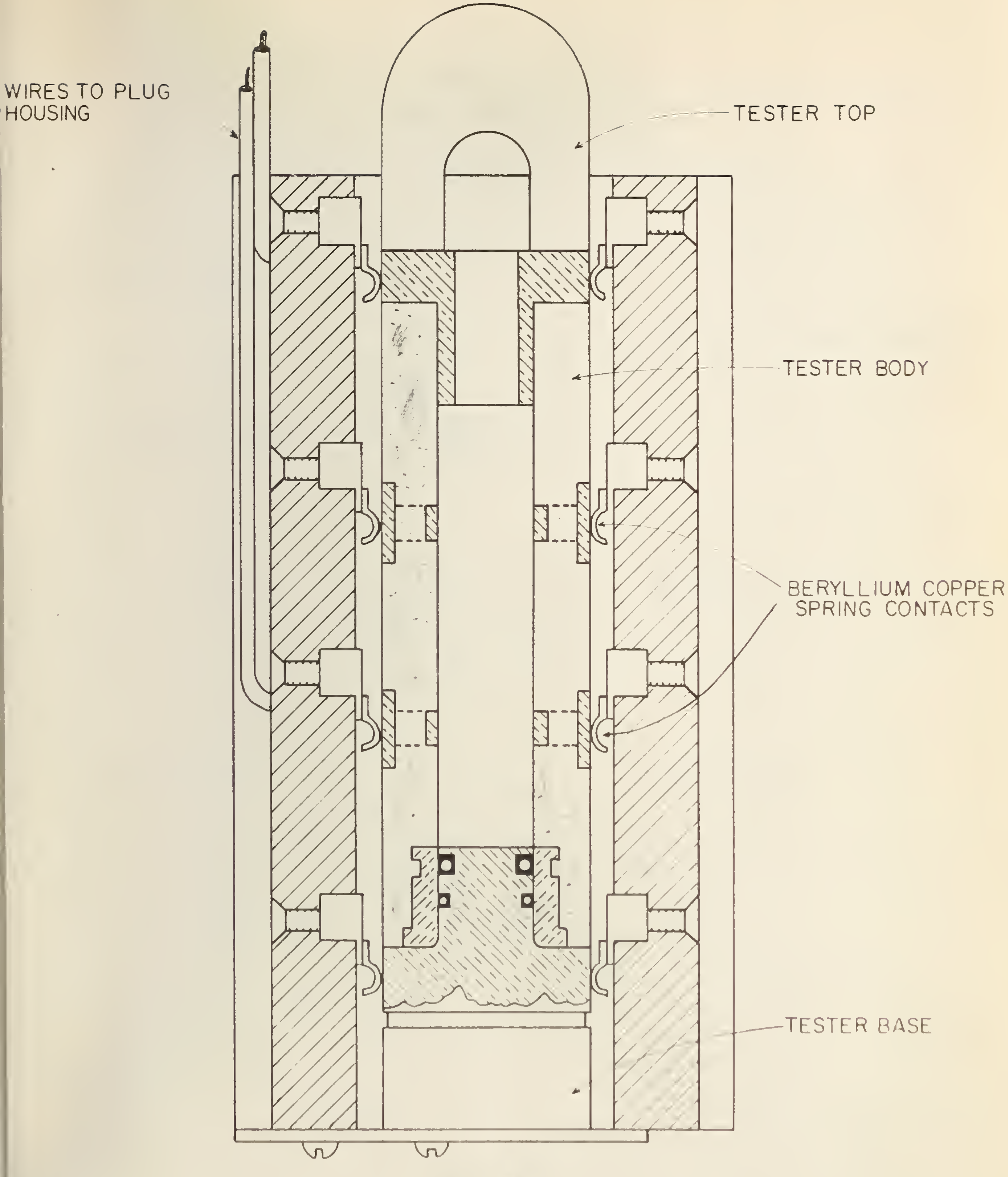

Fig. "3"

MUD FILTRATE TESTER IN CONTACTOR CASE

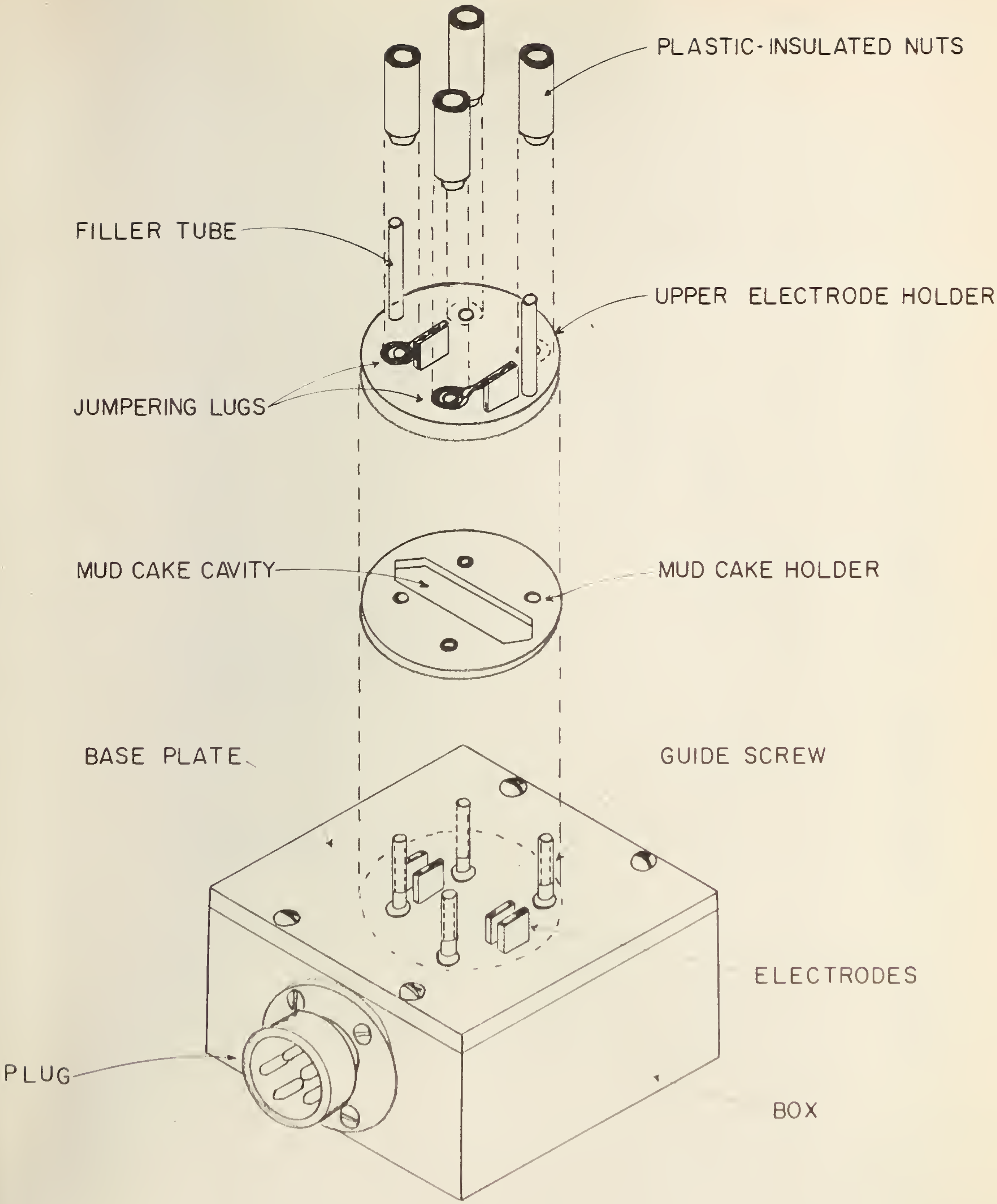

Fig. "4"

ASSEMBLY OF MUD CAKE TESTER

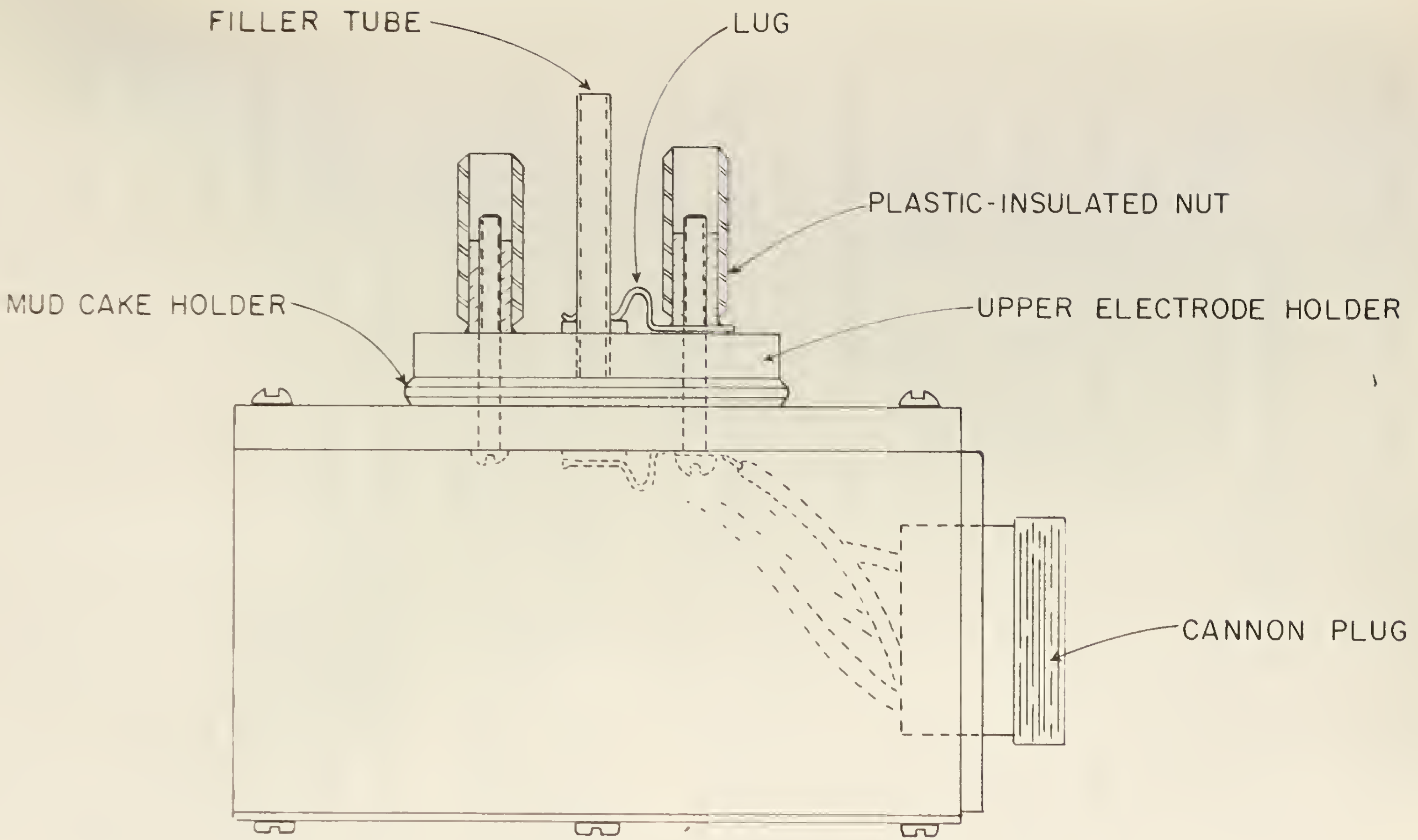

Fig. "5" MUD CAKE TESTER (Side View)

PART I -- RESISTIVITY OF OIL-EMULSION MUD

Variation of Resistivity with Oil-Content

Resistivity test runs on the first seven samples of Pembina oil-emulsion muds showed an unexpected trend. The samples with the higher oil contents invariably had lower electrical resistivities as is shown in Fig. 6. This is contrary to the generally accepted concept that the presence of oil in fresh water muds tends to increase their resistivity. Rogers[18] states that, "oil-emulsion muds may have a slightly higher resistance than fresh water muds but this fact is of no significant importance". Experimental work was required to establish the reason for the unexpected trend of gathered data.

Two series of tests were conducted. One of the series involved working with Edmonton tap water, while in the other a Pembina sample of oil-emulsion mud was used.

To form a stable oil-emulsion mud water, oil, bentonite and an emulsifier are thoroughly mixed together. During the mixing the oil is dispersed into minute globules which are held in suspension within the liquid phase of the mud. The stability of the emulsion is usually dependent upon the type and quantity of emulsifier present in the system. It has been suggested that the emulsifier interposes a tough film around oil droplets and thus

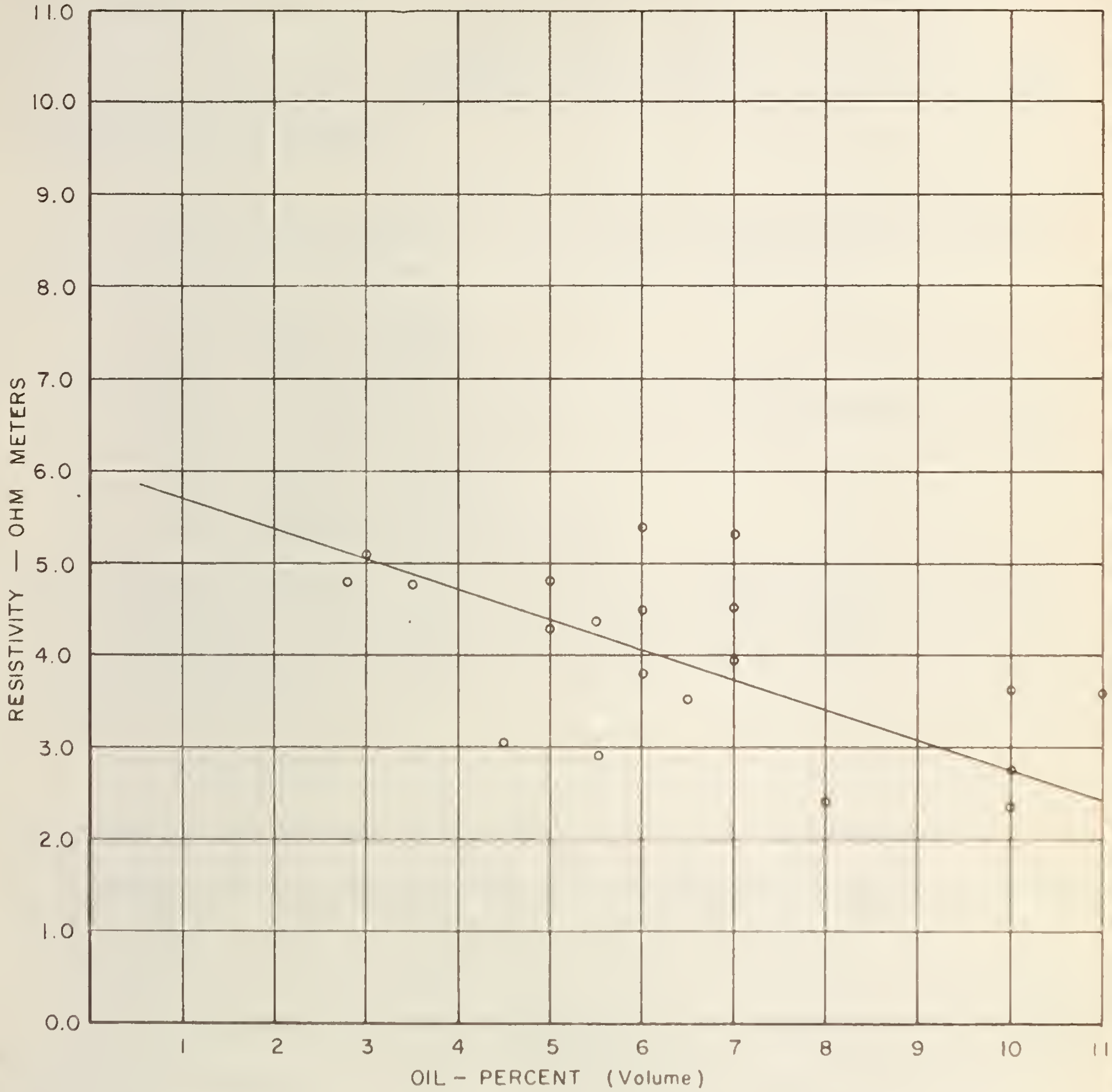

FIG. 6. VARIATION OF THE RESISTIVITY (80°F) OF SAMPLES OF PEMBINA OIL-EMULSION DRILLING FLUIDS WITH OIL CONTENT

prevents their coalescence. Also, it may be that certain ions are adsorbed on the surface of the tough film. In some instances these adsorbed ions may be so arranged that the oil globules repulse one another. This would add to emulsion stability.

The resistivity of oil-emulsion muds is a function of several variables. The major ones are:

1. oil content,
2. bentonite or other conducting-solids content,
3. water content,
4. emulsifier content,

The effects of these four variables on Edmonton tap water and on a sample of Pembina oil-emulsion mud were investigated.

The Effects of Diesel Fuel, Bentonite and a Commercial Emulsifier on the Resistivity of Edmonton Tap Water

The resistivity of Edmonton tap water increased from 40.0 ohm-meters to 93.0 ohm-meters when its diesel fuel content was increased stepwise from 0 to 48%. Stirring and mixing conditions were kept identical throughout and the resistivity measurements were corrected to a temperature base of 75°F.

A 4%-bentonite slurry made from the same water had a resistivity of 9.0 ohm-meters @ 75°F. The resist-

ivity of the water-bentonite system was reduced further as the bentonite content was increased. A 10%-bentonite slurry had a resistivity of only 4.9 ohm-meters @ 75°F.

Increasing percentages of diesel fuel alone were added to different bentonite slurries. In all cases the resistivity of the system was increased only slightly.

Last of all Emulsite, a commercial emulsifier, was added to a bentonite-diesel-water system. This addition effected a marked reduction in the resistivity of the system. Table 1 contains the test results, and Fig. 7 shows the contrast between the effects of diesel fuel, and bentonite, and an emulsifier on the resistivity of Edmonton tap water.

For quick comparison of the experimental data given in Table 1, the following summary is presented:

Water %	Diesel Fuel %	Bentonite %	Emulsifier %	Resistivity @ 75°F ohm-meters	Remarks
100.0	---	---	---	40.0	Edmonton Tap Water
92.0	8.0	---	---	44.50	
96.0	---	4.0	---	9.00	
88.0	8.0	4.0	---	9.10	
88.0	8.0	4.0	2.0	5.40	

Note: 600 cc. of mixture used for each resistivity measurement.

Table 1 --The Effects of Bentonite, Diesel Fuel and an Emulsifier on Water Resistivity @ 75° F.

Run #	Bentonite %	Diesel Fuel %	Water %	Emulsifier grams	Resistivity @ 75° F. ohm-meters
1	---	---	100	---	40.00
	---	4.0	96.0	---	42.00
	---	8.0	92.0	---	44.50
	---	12.0	88.0	---	47.50
	---	16.0	84.0	---	51.50
2	---	24.0	76.0	---	58.50
	---	32.0	68.0	---	66.50
	---	40.0	60.0	---	80.00
	---	48.0	52.0	---	93.00
	---	56.0	44.0	---	too high
3	4.0	----	96.0	---	9.00
	6.0	----	96.0	---	6.90
	10.0	----	96.0	---	4.90
4	4.0	8.0	88.0	---	9.10
	6.0	8.0	88.0	---	7.30
	7.5	8.0	88.0	---	6.15
	10.0	8.0	88.0	---	5.40
5	4.0	16.0	80.0	---	9.30
	6.0	16.0	80.0	---	7.80
	7.5	10.0	80.0	---	6.50
	10.0	10.0	80.0	---	could not be obtained
6	6.0	24.0	70.0	---	9.50
	6.0	32.0	62.0	---	9.90
7	4.0	8.0	88.0	---	9.10
	4.0	8.0	88.0	2.0	5.40
	4.0	8.0	88.0	4.0	4.05
	4.0	8.0	88.0	6.0	3.15
	4.0	8.0	88.0	8.0	2.70

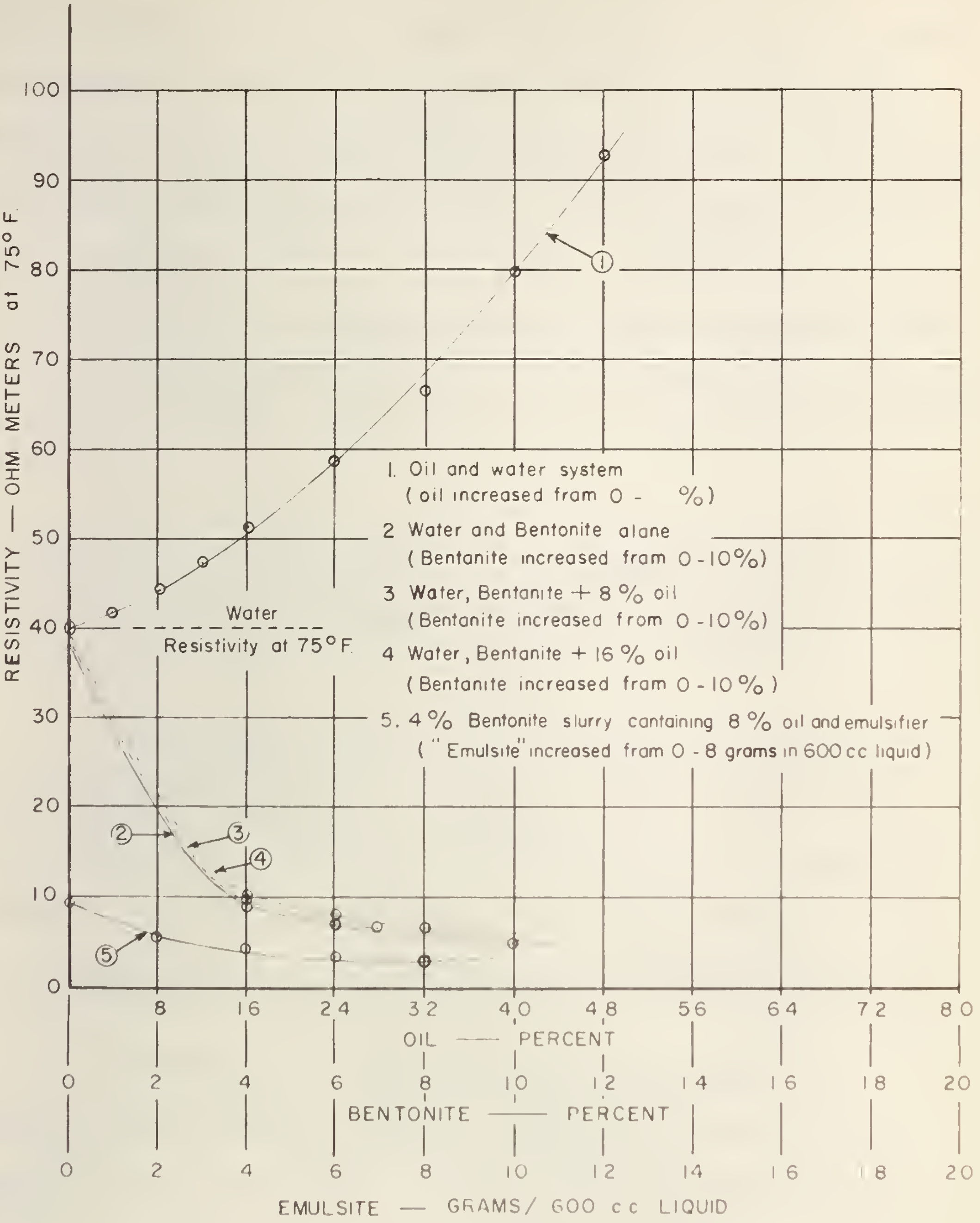

FIG 7 THE EFFECTS OF VARYING CONCENTRATIONS OF DIESEL FUEL, BENTONITE AND EMULSIFIER ("EMULSITE") ON THE RESISTIVITY OF EDMONTON TAP WATER

This summary of the data indicates that an addition of diesel fuel to water to give an oil content of 8% increases the resistivity of the system by about 11%. However, the same addition of diesel fuel to a 4%-bentonite slurry increases the resistivity of the system by about 1% only. It should also be noted that an addition of 2.0 gms. of Emulsite to a 4%-bentonite slurry containing 8% diesel fuel reduced the resistivity of the system by about 40.5%.

The Effects of Diesel Fuel and a Commercial Emulsifier on the Resistivity of a Sample of Pembina Oil-Emulsion Mud

The sample used for this series of investigations had an original oil content of only 2.0% and its solid content was 7%. Its resistivity was 9.0 ohm-meters @ 80°F. This high resistivity value was probably caused by the unusually low ion content of the water phase.

Additions of diesel fuel to increase the volumetric oil content from 0 - 25% in this mud sample increased its resistivity from 9.0 ohm-meters to 18.0 ohm-meters @ 80°F, as shown in Table 2 and Fig. 8. Mixing conditions were kept identical throughout and all resistivity measurements were corrected to a temperature base of 80°F.

Next, to simulate field practice, both the diesel fuel and the emulsifier were added in increasing quantities, to a fresh portion of the sample. The system which contained the maximum amount of emulsifier had the lowest resistivity, irrespective of the fact that its oil content was high.

Lastely, to another fresh portion of the sample, increasing amounts of emulsifier alone were added. The resistivity of the system was reduced to its lowest value for this over-all series of runs on Sample 24. The experimental data are presented in Table 2 and Fig. 8. Significant data from Table 2 may be summarized as follows:

Field Sample	Diesel Fuel Added %	Emulsite Added Gm.	Resistivity ohm-meters @ 75°F	Remarks
#24	---	---	9.00	Oil content of this sample: 2.% Solid content of this sample: 4.%.
#24	10.0	---	11.70	
#24	10.0	4.0	5.40	
#24	---	4.0	4.60	

Note: 600 cc. of mixture was used for each measurement.

The above data indicate that the addition of 10% diesel fuel to the original mud sample increased its

Table 2 -- The Effects of Diesel Fuel, Diesel Fuel and Emulsite, and Emulsite Alone on the Resistivity of a Sample of Pembina Oil-Emulsion Drilling Fluid.

Sample #	Run #	Oil Percent	Dispersant gms.	R_m Ohmmeter	Temp. °F.
24	I	---	---	9.0	80°
	II	5.0	---	10.0	80°
		10.0	---	11.7	"
		15.0	---	13.5	"
		20.0	---	15.5	"
		25.0	---	18.0	"
	III	5.0	2.0	6.50	80°
		10.0	4.0	5.40	"
		15.0	6.0	4.55	"
		20.0	8.0	4.10	"
		25.0	10.0	3.50	"
	IV	---	2.0	5.70	80°
		---	4.0	4.60	"
		---	6.0	3.70	"
		---	8.0	3.00	"
		---	10.0	2.50	"

Sample 24 -- Socony-Seaboard Violet Grove #20-14

Location: 14-20-48-7W5

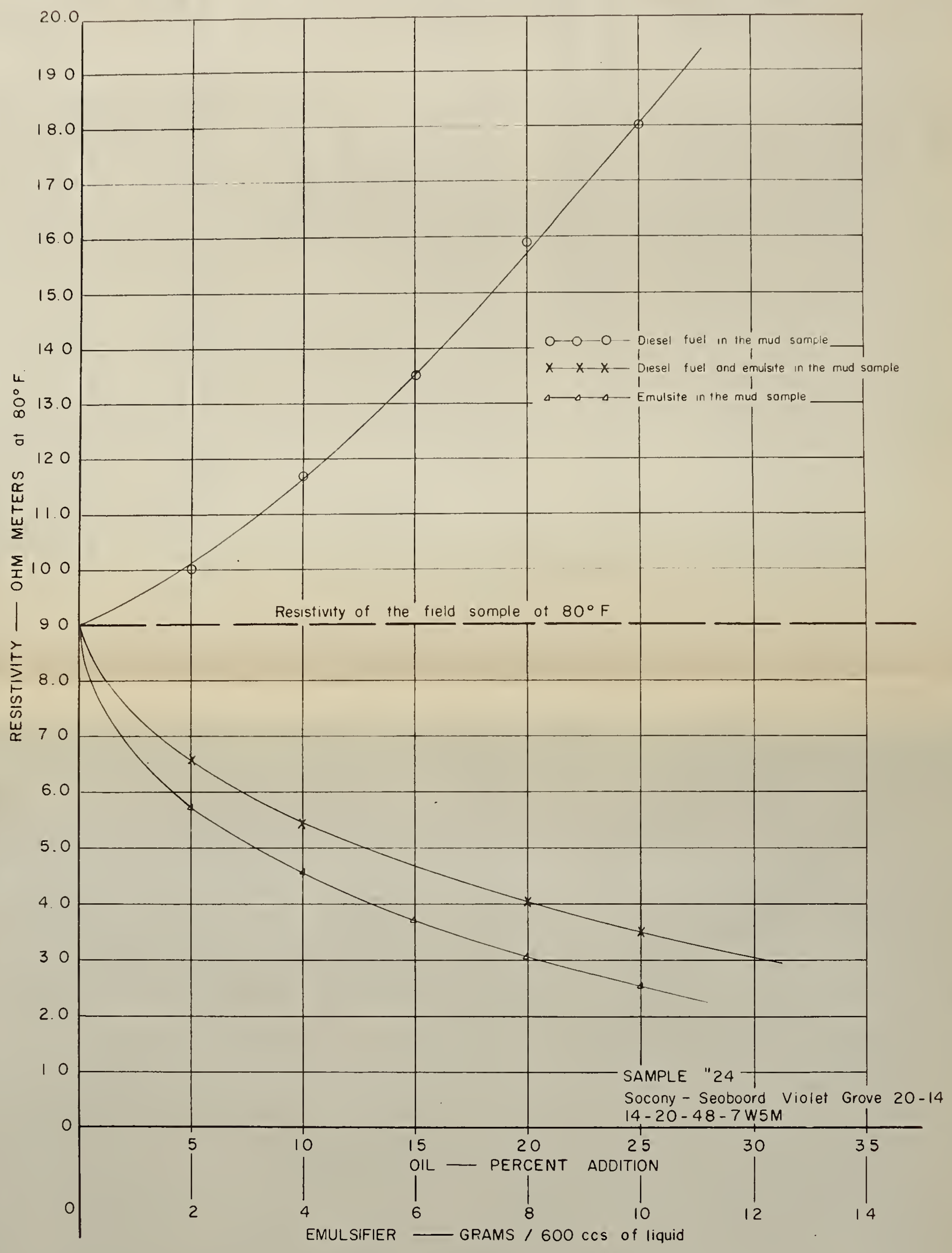

FIG. 8. THE EFFECTS OF VARYING CONCENTRATIONS OF DIESEL FUEL, DIESEL + "EMULSITE" AND "EMULSITE" ALONE ON THE RESISTIVITY OF A FIELD SAMPLE OF PEMBINA OIL-EMULSION DRILLING FLUID

resistivity by about 30%. On the other hand, 4.0 grams of Emulsite added alone to the original mud reduced the resistivity of the system by about 49%. It may, however, be noted that 4.0 grams of Emulsite added with the 10% diesel fuel to the original system reduced the resistivity of the system by about 40%. This 9.0% decrease in the reduction of the resistivity of the system is due to the addition of oil with the emulsifier.

The Effects of Various Commercial Emulsifiers on the Resistivity of Edmonton Tap Water

Three commercial emulsifiers employed to convert fresh-water muds into oil-emulsion muds are:

1. Carbonox with sodium hydroxide (NaOH)
2. Speedy Drill--a trade name of a commercial emulsifier.
3. Emulsite--a trade name of a commercial emulsifier.

Both Speedy-Drill and Emulsite contain sodium hydroxide. The over-all composition of these emulsifiers is a trade secret.

Carbonox is not easily soluble in fresh water unless sodium-hydroxide is added to the mixture. However, to isolate the effect of the addition of sodium-hydroxide on the resistivity of water which forms the

Table 3 -- The Effect of Various Commercial Emulsifiers and Diesel Fuel on the Resistivity of Edmonton Tap Water

Run #	Type Emulsifier Used	Amount of Emulsifier Used grams	Oil %	Water %	Resistivity @ 80° F ohm-meters
1		---	---	100.0	39.00
2	CARBONOX	2.00	---	100.0	18.20
		4.00	---	100.0	14.00
		6.00	---	100.0	11.20
		8.00	---	100.0	8.80
		10.00	---	100.0	7.60
3		2.00	5.0	95.0	20.00
		4.00	10.0	90.0	16.00
		6.00	15.0	85.0	12.50
		8.00	20.0	80.0	10.00
		10.00	25.0	75.0	8.70
4	SPEEDY DRILL	2.00	---	100.0	10.50
		4.00	---	100.0	8.00
		6.00	---	100.0	5.90
		8.00	---	100.0	4.60
		10.00	---	100.0	3.90
5		2.00	5.0	95.0	11.20
		4.00	10.0	90.0	8.60
		6.00	15.0	85.0	6.40
		8.00	20.0	80.0	5.10
		10.00	25.0	75.0	4.20
6	EMULSITE	2.00	---	100.0	7.30
		4.00	---	100.0	4.20
		6.00	---	100.0	3.00
		8.00	---	100.0	2.15
		10.00	---	100.0	1.60
		2.00	5.0	95.0	7.70
		4.00	10.0	80.0	4.70
		6.00	15.0	85.0	3.50
		8.00	20.0	80.0	2.60
		10.00	25.0	75.0	2.00

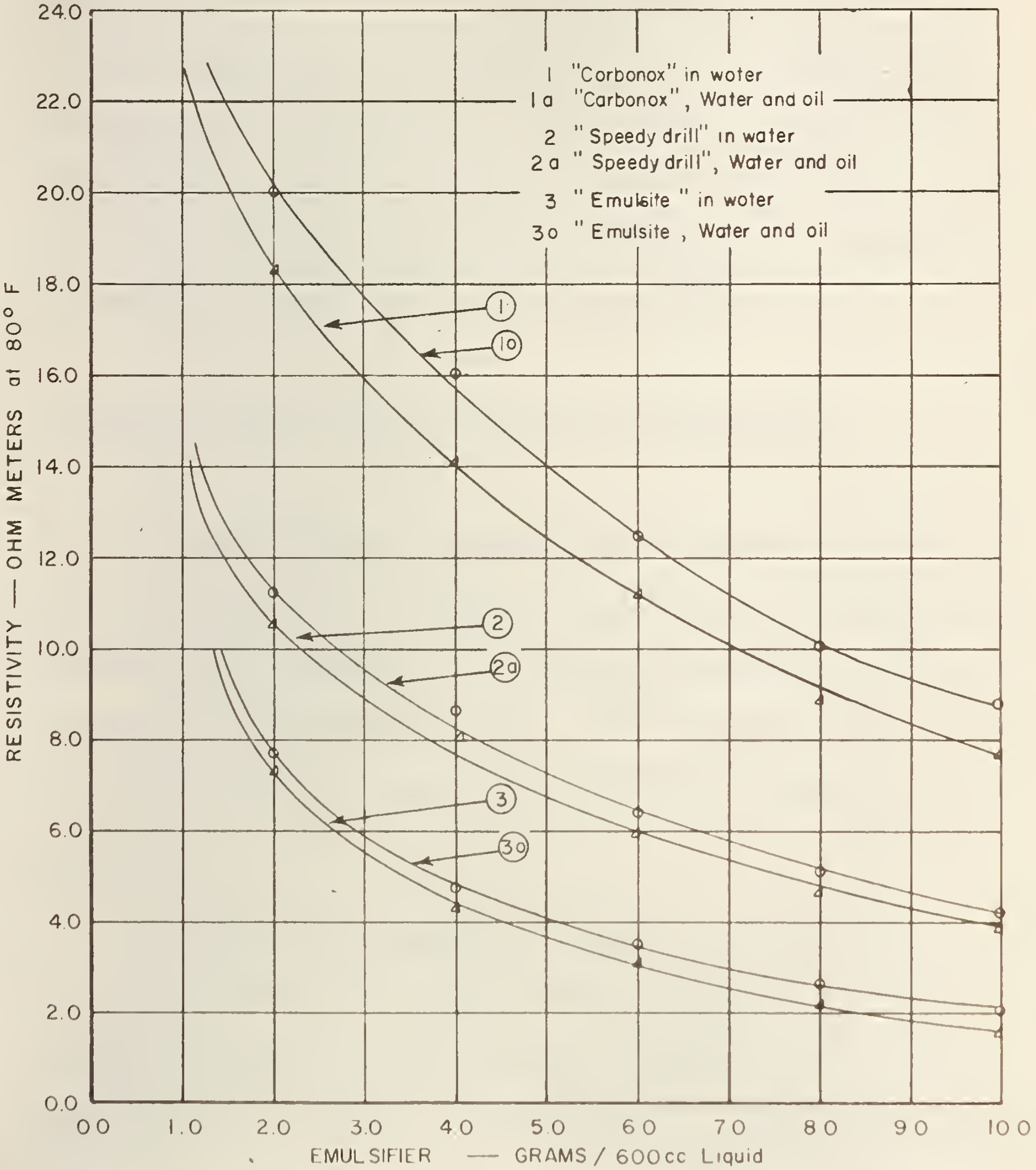

FIG 9 THE EFFECT OF DIFFERENT COMMERCIAL EMULSIFIERS ON THE RESISTIVITY. OF "WATER" AND "WATER AND OIL" SYSTEMS.

base of almost all the commercial emulsifiers, carbonox was added alone. Addition of the carbonox alone did effect a marked reduction in the resistivity of water, but the reduction was not as great as in the case of Speedy Drill or Emulsite. The results of this set or experimental runs are given in Table 3, and Fig. 9 compares the effects of Carbonox, Speedy Drill and Emulsite on the resistivity of Edmonton tap water.

Variation of Mud Resistivity With Temperature

The effect of temperature increase on the resistivities of oil-emulsion muds was investigated on fourteen field samples. Resistivity-temperature plots for some of these samples are shown in Fig. 10. Table A-3 contains the temperature resistivity data of these samples.

Fig. 11 shows the effect of temperature on both the resistivities of Pembina field-samples and those of standard sodium-chloride brines. Results are plotted side by side for ease of comparison. Resistivity values of sodium chloride brines at high temperatures, as contained in Table A-4, were obtained from SWSCO Log Interpretation Charts.

Effect of temperature on the resistivity of oil-emulsion mud is comparable to that on the sodium chloride

brines. A hundred per cent increase in temperature reduces the resistivity of the mud by about 50% of its original value.

The Arps' formula, previously presented, was used in this investigation to calculate the values of mud resistivities at higher temperatures. The computed values were compared with those obtained experimentally.

It was found that resistivity values estimated by Arps' formula were higher than those obtained experimentally. Also, it was found that at 160°F, the difference in the calculated and measured values was greater than that at 120°F. However, Arps'[2] points out that his approximation formula gives values of resistivity at temperatures below 150°F which are above the true values.

In an effort to adjust the Arps' formula so that it would more nearly describe the trend of the experimental data, the resistivity-ratio $\frac{(R_m)t_1}{(R_m)t_2}$ was plotted against temperature t°F. The plot is shown in Fig. 12. From the plot it may be noted that the variations of the resistivity ratios at a given temperature are only slight. Arps' formula and adjusted forms of the formula are shown below:

$$\frac{(R_w)t_2}{(R_w)t_1} = \frac{t_1 + 7}{t_2 + 7} \quad \text{(By Arps)} \qquad (1)$$

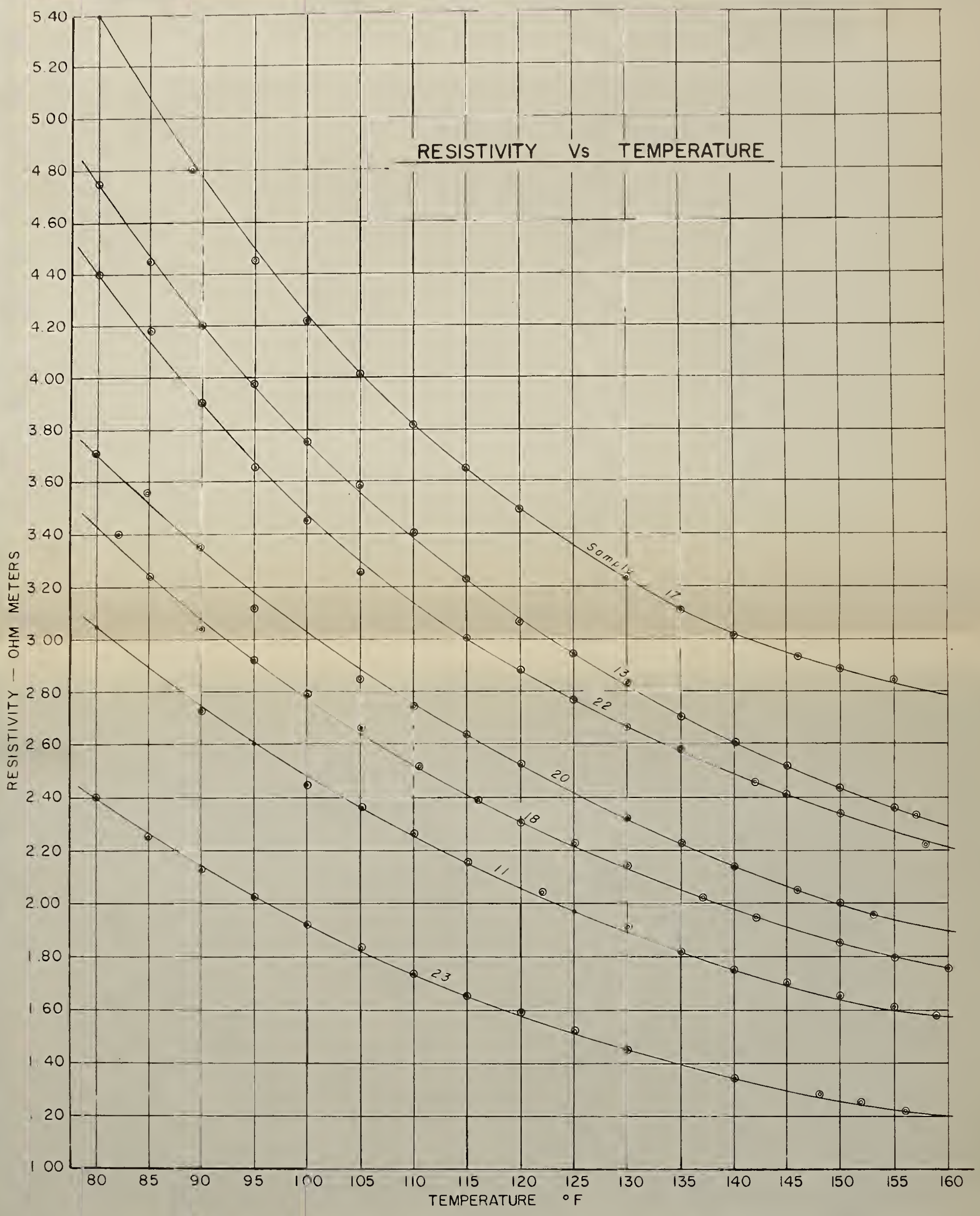

FIG. 10. THE EFFECT OF TEMPERATURE INCREASE ON THE RESISTIVITY OF SAMPLES OF PEMBINA OIL-EMULSION DRILLING FLUIDS

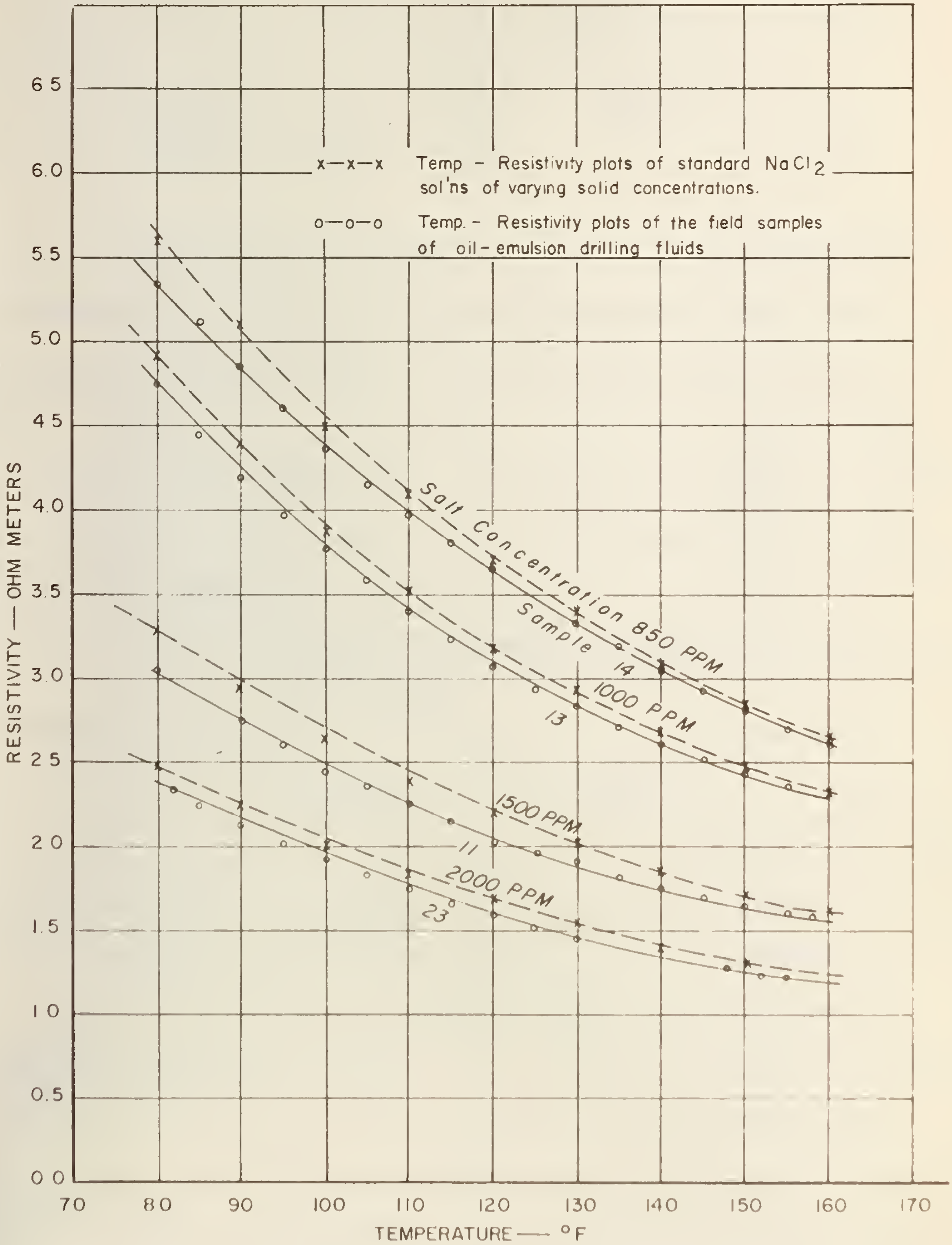

FIG 11 COMPARISON OF THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF PEMBINA OIL-EMULSION DRILLING FLUIDS AND THAT OF SODIUM CHLORIDE BRINES.

$$\left.\begin{array}{ll} \dfrac{(R_m)t_2}{(R_m)t_1} = \dfrac{t_1 + 2}{t_2 + 2} & \\ & \\ \dfrac{(R_m)t_2}{R_m\ t_1} = \dfrac{t_1}{t_2} & \end{array}\right\} \begin{array}{c} \text{Adjusted} \\ \text{Forms} \end{array} \quad \begin{array}{c} (2) \\ \\ (3) \end{array}$$

Measured and calculated resistivity-ratios for a Pembina oil-emulsion drilling fluid (Sample 23) are contained in Table 5 and are shown plotted on Fig. 13. Table 4 compares the experimental values of resistivities obtained at 120°F with those obtained by the above formula. The percentage deviations between calculated and measured resistivity values are shown below:

Formula Used	Ave. Difference in Calculated and Experimental values %		Remarks
	@ 120°F	@ 160°F	
$\dfrac{(R_w)t_2}{(R_w)t_1} = \dfrac{t_1 + 7}{t_2 + 7}$	+ 3.90	+ 4.18	Average of 14 samples of Pembina oil-emulsion drilling fluids
$\dfrac{(R_m)t_2}{(R_m)t_1} = \dfrac{t_1 + 2}{t_2 + 2}$	+ 1.89	+ 1.18	
$\dfrac{(R_m)t_2}{R_{mt_1}} = \dfrac{t_1}{t_2}$	+ 1.21	+ 0.01	

Elimination of the constant from Arps' formula decreases the relatively large differences between the measured and predicted values of resistivities. For field practice in connection with Pembina oil-emulsion drilling fluids formula 3 appears useful.

Variation of Mud Resistivity with Temperature and Pressure

The effect of high pressure on the resistivity of mud was investigated on four samples of Pembina oil-emulsion muds. In the case of the first field sample, the pressure on the mud was increased up to 800 psig in stages. The resistivity was recorded at each increment of the pressure. For each of the remaining three samples, mud was heated gradually from 80° F. to 160° F. in the Ruska temperature bath. After every 5° F. rise in temperature, the pressure was increased up to 800 psig in stages and the resistivity of the mud recorded at every increment of the pressure. No change in the resistivity of the mud was detected by pressure alone. Table 6 contains the results of this investigation and Fig. 14 shows the resistivity variations of these mud samples with temperature.

TABLE 4. COMPARISON OF MEASURED AND PREDICTED RESISTIVITIES FOR PEMBINA OIL-EMULSION DRILLING FLUIDS

FIELD SAMPLE	Rm Ohm meters at 80°F	RmE (ohm meters) at t° F		RmA (ohm meters) at t° F		Rm A' (ohm meters) at t° F		RmA'' (ohm meters) at t° F		PERCENT DIFFERENCE					
		120°	160°	120°	160°	120°	160°	120°	160°	$\frac{Rm120°A - Rm120°E}{Rm120°E}$	$\frac{Rm160°A - Rm120°E}{Rm160°E}$	$\frac{Rm120°A' - Rm120°E}{Rm120°E}$	$\frac{Rm160°A' - Rm160°E}{Rm160°E}$	$\frac{Rm120°A'' - Rm120°E}{Rm120°E}$	$\frac{Rm160°A'' - Rm160°E}{Rm160°E}$
9	2.35	1.60	1.20	1 61	1.22	1.59	1.19	1.57	1.17	+ 0.62	+ 1.66	− 0.62	− 0.83	− 1.87	− 2.50
10	5.10	3.25	2.59	3.49	2.66	3.43	2.58	3.40	2.55	+ 7.38	+ 2.70	+ 5.50	− 0.39	+ 4.61	− 1.54
11	3.05	2.06	1.57	2.09	1.59	2.05	1.54	2.03	1.52	+ 1.45	+ 1.27	− 0.48	− 1.91	− 1.46	− 3.29
13	4.75	3.07	2.30	3.25	2.47	3.19	2.40	3.17	2.37	+ 5.86	+ 7.39	+ 3.90	+ 4.35	+ 3.25	+ 3.04
14	5.35	3 65	2.60	3.66	2.79	3.59	2.70	3.57	2.67	+ 0.27	+ 7.31	− 1.64	− 3.85	− 2.19	+ 2.69
15	4.50	3.00	2.36	3.08	2.34	3.02	2.28	3.00	2.25	+ 2.66	− 0.85	− 0.66	+ 3 39	− 0.00	− 4.66
16	4.79	3.20	2.30	3.28	2.49	3.22	2.42	3.19	2.39	+ 2.50	+ 8.26	+ 0.62	− 5.21	− 0.31	+ 3.91
17	5.40	3.50	2.80	3.70	2.81	3.62	2.73	3.60	2.70	+ 5.71	+ 0.36	+ 3.42	+ 2.50	+ 2.86	− 3.57
18	.3.50	2.30	1.75	2.39	1.82	2.35	1.77	2.33	1.75	+ 3.91	+ 2.86	+ 2.17	− 1.14	+ 1.30	+ 0.00
19	3.95	2.56	1.92	2.70	2.06	2.65	1.99	2.63	1.97	+ 5.47	+ 7.29	+ 3 39	+ 3 64	+ 2.73	+ 2.60
20	3 80	2.52	1.92	2.60	1.98	2.55	1.92	2.53	1.90	+ 3.17	+ 3.12	+ 1.19	+ 0.00	+ 0.39	− 1.04
21	4.45	2.82	2.13	3.05	2.32	2.99	2.25	2.97	2.22	+ 8.15	+ 8.92	+ 6.02	+ 5.63	+ 5.32	+ 4.22
22	4.40	2.88	2.20	3.01	2.29	2.95	2.22	2.93	2.20	+ 4.51	+ 4.09	+ 2.43	+ 0.91	+ 1.74	+ 0.00
23	2.40	1.59	1.20	1.64	1.25	1.61	1.21	1.60	1.20	+ 3.14	+ 4.17	+ 1.26	+ 0.83	+ 0.63	+ 0.00
										AVERAGE PERCENT DIFFERENCE					
										+ 3.90	+ 4.18	+ 1.89	+ 1.18	+ 1.21	− 0.01

NOTES RmE = Experimental values of resistivity with temperatures

RmA = Predicted values of resistivity by the use of ARPS' formula $(RW)tg = (RW)t_1 \frac{t_1+7}{t_2+7}$

RmA' = Predicted values of resistivity by $(Rm)t_2 = (Rm)t_1 \frac{t_1+2}{t_2+2}$ (Same as ARPS' formula but derived from the temp - res data of Pembina oil-emulsion drilling fluids)

RmA'' = Predicted values of resistivity by $(Rm)t_2 = Rmt_1 \frac{t_1}{t_2}$ (Same as above but without constant "2")

TABLE 5. COMPARISON OF MEASURED AND PREDICTED RESISTIVITIES FOR PEMBINA OIL-EMULSION DRILLING FLUID (SAMPLE 23)

FIELD SAMPLE	RESISTIVITY — OHM METERS at t° F									(Rmt) / (Rm)t - VALUES								REMARKS
	80°	90°	100°	110°	120°	130°	140°	150°	160°	$80°/90°$	$80°/100°$	$80°/110°$	$80°/120°$	$80°/130°$	$80°/140°$	$80°/150°$	$80°/160°$	
23	2.40	2.13	1.92	1.74	1.59	1.47	1.37	1.27	1.20	1.127	1.250	1.380	1.509	1.633	1.752	1.890	2.000	Experimental values
	2.40	2.15	1.95	1.78	1.64	1.52	1.42	1.33	1.25	1.116	1.231	1.348	1.463	1 579	1.690	1.804	1.920	Predicted values by $(RW)t_2 = (RW)t_1 \frac{t_1+7}{t_2+7}$
	2.40	2.14	1.93	1.75	1.60	1.47	1.38	1 28	1.21	1.121	1 243	1.370	1 491	1 611	1.739	1 800	1.983	Predicted values by $(Rm)t_2 = (Rm)t_1 \frac{t_1+2}{t_2+2}$
	2 40	2 13	1 92	1.74	1 60	1.47	137	1.28	1 20	1.127	1 250	1.380	1 500	1 633	1.752	1.875	2.000	Predicted values by $(Rm)t_2 = Rmt_1 \frac{t_1}{t_2}$

NOTES:

1 $(RW)t_2$ = Predicted resistivity of sodium chloride brine at temperature t_2° F

2 $(RW)t_1$ = Known resistivity of sodium chloride brine at temperature t_1° F

3 $(Rm)t_1$ = Known resistivity of oil-emulsion mud at temperature t_1° F.

4 $(Rm)t_2$ = Predicted resistivity of oil-emulsion mud at temperature t_2° F

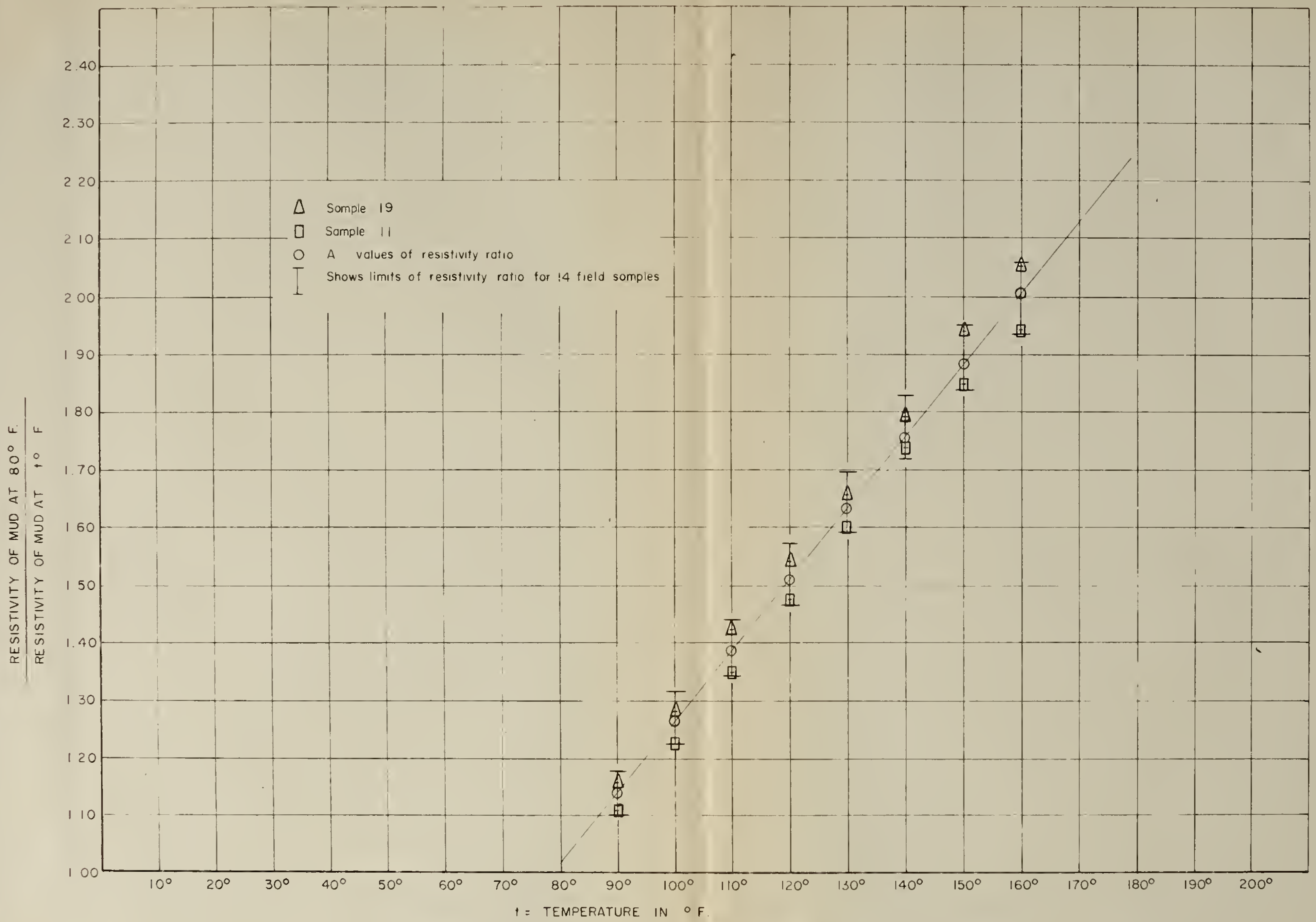

FIG. 12 VARIATION OF RESISTIVITY RATIOS WITH TEMPERATURE FOR PEMBINA OIL-EMULSION DRILLING FLUIDS.

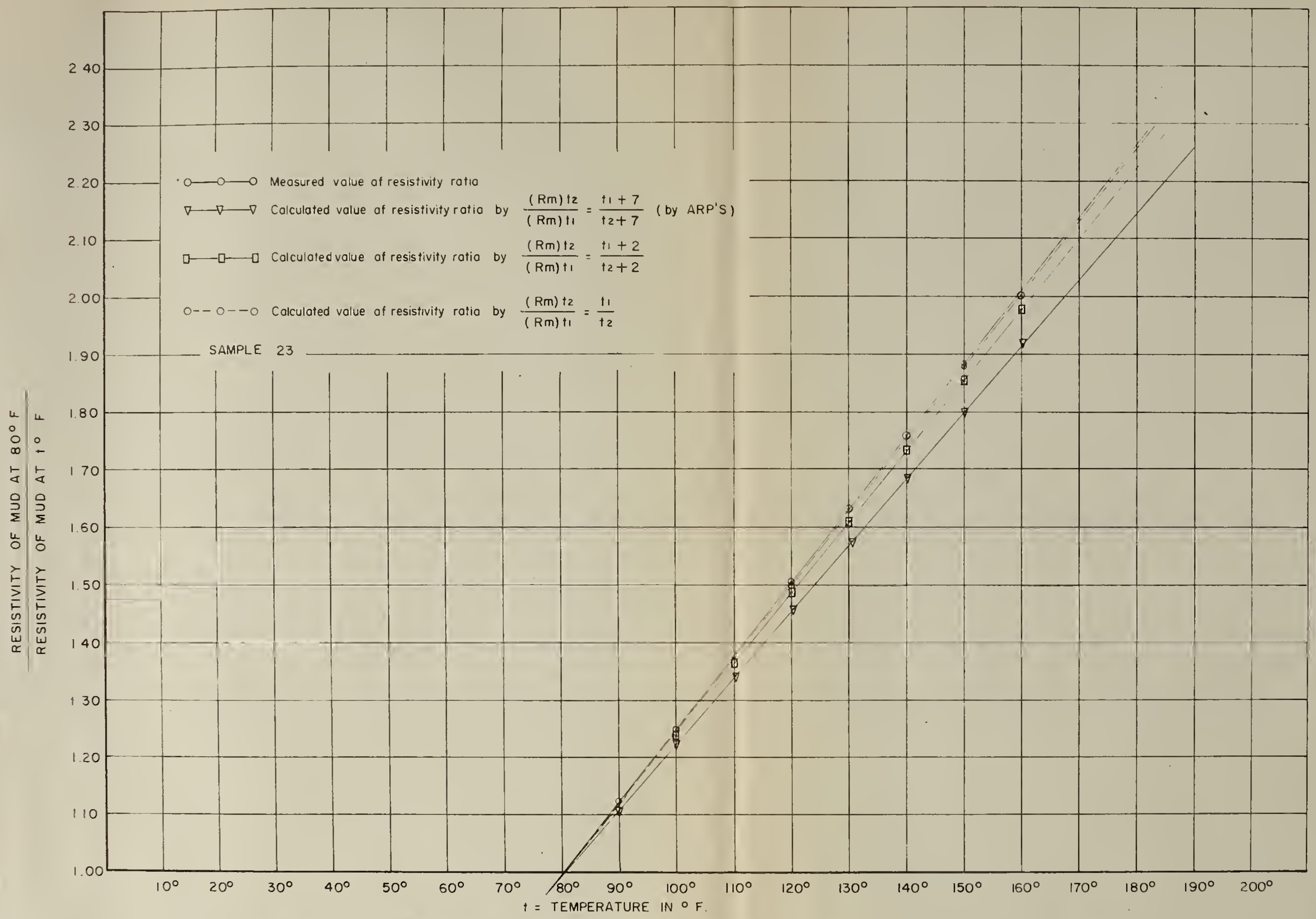

FIG. 13 COMPARISON OF MEASURED AND CALCULATED RESISTIVITY RATIOS FOR A PEMBINA OIL-EMULSION DRILLING FLUID.

TABLE 6. VARIATION OF THE RESISTIVITIES OF PEMBINA OIL-EMULSION DRILLING FLUIDS WITH PRESSURE AND TEMPERATURE

SAMPLE	Temperature °F	Resistivity at Pressures							
		14.5 PSI	125 PSI	250 PSI	375 PSI	500 PSI	600 PSI	700 PSI	800 PSI
A	78°	5.20	5.15	5.15	5.15	5.20	5.20	5.20	5.20
B	88°	3.70							
	86°	3.80	3.80	3.80	3.80	2.10	2.10	2.10	2.10
	86°	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80
	87.5°	3.75	3.75	3.75	3.75	3.75	3.75		
	101°	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
	107°	3.27	3.27	3.27	3.27	3.27	3.27		
	114°	3.03	3.03	3.03	3.03	3.03			
	117.5°	2.90							
	122°	2.75							
	127°	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58
	131°	2.42							
	136.5°	2.30	2.30	2.30	2.30	2.30	2.30	2.30	
	144°	2.12	2.12	2.12	2.12	2.12	2.12	2.12	
	147.5°	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07
C	80°	6.95	6.95	6.95	6.95	6.95	6.95	6.95	6.95
	81°	6.90	6.90	6.90	6.90	6.90	6.90	6.90	6.90
	85°	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60
	90°	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
	95°	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95
	100°	5.60	5.60	5.60	5.60	5.60	5.60	5.60	5.60
	105°	5.30	5.30	5.30	5.30	5.30	5.30	5.30	5.30
	110°	5.05	5.05	5.05	5.05	5.05	5.05	5.05	5.05
	115°	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80
	120°	4.55	4.55	4.55	4.55	4.55	4.55	4.55	4.55
	125°	4.35	4.35	4.35	4.35	4.35	4.35	4.35	4.35
	130°	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
	135°	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	140°	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
	145°	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72
	150°	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
	156°	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48
	160°	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40
D	80°	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85
	84°	5.60	5.60	5.60	5.60	5.60	5.60	5.60	5.60
	90°	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20
	95°	4.93	4.93	4.93	4.93	4.93	4.93	4.93	4.93
	100°	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68
	105°	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42
	110°	4.20	4.20	4.20	4.20	4.20	4.20	4.20	4.20
	115°	3.99	3.90	3.90	3.90	3.90	3.90	3.90	3.90
	120°	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
	130°	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
	135°	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27
	140°	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14
	145°	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	150°								
	160°	2.90	Extrapolated value						

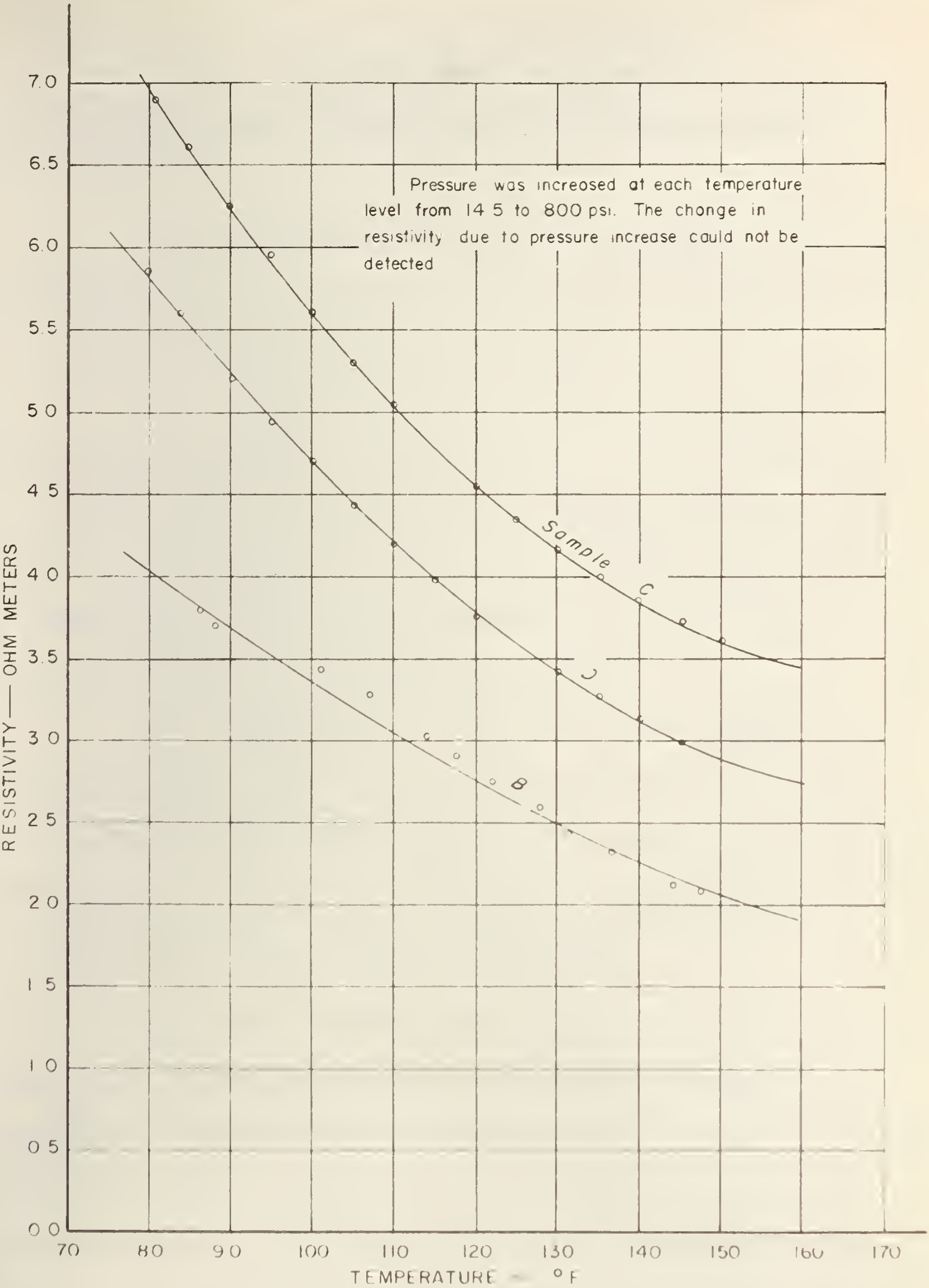

FIG 14, THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF OIL-EMULSION MUD SAMPLES WHICH WERE PERIODICALLY SUBJECTED TO ELEVATED PRESSURES

PART II -- RESISTIVITIES OF FILTRATES AND FILTER CAKES OBTAINED FROM OIL-EMULSION MUDS

As mentioned earlier in this thesis, the resistivities of the mud filtrate or mud filter cake are obtained by one of the following two methods:

1. If the resistivity of the mud at surface temperature is known, the resistivity of its filtrate or its filter cake is obtained from temperature-correction charts. The experimental data used in the construction of these charts have been obtained in the laboratory on samples of fresh water-clay base muds.
2. Filtrate and filter cake are obtained from the field sample and their resistivities are measured on the equipment described earlier. The choice of filtration temperature and filtration pressure is made usually only to offer convenience in the laboratory.

The first method gives values of resistivities which are only approximate and can lead to large errors. A study of the electrical characteristics of the filtrates and filter cakes suggests that filtration pressure and temperature are important variables. Filtration pressure tends to change the chemical, electrical and physical characteristics of filtrates. The effect of filtration temperature on filtrate and cake resistivities, however,

was so small that it could not be detected.

Data from this phase of the investigation lead to the following observations:

1. Resistivity of high-pressure* filtrate is higher than that of a low-pressure** filtrate.
2. The difference in the resistivities of high and low-pressure filtrates seems to depend on the original resistivity of the mud. Muds with higher resistivities usually show greater differences in their filtrate resistivities. This behaviour does not hold true if the break-down of emulsions occurred during high-pressure and high-temperature filtration.
3. The pH of high-pressure filtrate is invariably lower than that of low-pressure filtrate.
4. High-pressure filtrate is always lighter in color than the low-pressure filtrate of the same mud.
5. Solid concentrations of high-pressure filtrate is lower than that of the low-pressure filtrate of the same mud.
6. Resistivities of both high and low-pressure filtrates are related to the resistivity of the mud but are generally less than R_m.

* 1000 P.S.I.G. across cake

** 100 P.S.I.G. across cake

7. Mud cake resistivities are related to their mud resistivities. On the average, Mud Cake resistivities seem to be greater than the mud resistivities.
8. High-pressure mud cake usually has a lower resistivity than the low-pressure mud cake obtained from the same mud. There are exceptions.
9. High-pressure and high-temperature tend to break down the emulsions of some muds.
10. Both high filtration pressure and high filtration temperature increase the filtration rate of oil-emulsion muds.

The physical and chemical reasons for these results are of interest.

Resistivities of Filtrates Obtained at Different Filtration Pressures

High-pressure filtrate has invariably a higher resistivity than the low-pressure filtrate of the same mud. The average difference in their resistivities as obtained on 23 Samples of Pembina oil-emulsion drilling fluids is + 6.2 per cent. A minimum difference of + 2.1% and a maximum of + 12.35% were obtained (Table 7).

Since the resistivity of oil-emulsion drilling fluid depends upon a number of variables, this persistent

TABLE 7 COMPARISON OF ELECTRICAL AND CHEMICAL CHARACTERISTICS OF FILTRATES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS AT HIGH AND LOW PRESSURES

FIELD SAMPLE	OIL PERCENT	Rm	RmfH	RmfL	RmfH-RmfL	$\frac{RmfH \cdot RmfL}{RmfH}$	$\frac{RmfH}{Rm}$	$\frac{RmfL}{Rm}$	pH of High Pressure Filtrate	pH of Low Pressure Filtrate
1	11.0	3.60	2.33	2.16	+ 0.17	7.30	0.647	0.600	9.40	9.90
2	6.0	4.55	3.87	3.58	+ 0.29	8.10	0.850	0.787	8.45	8.70
3	5.0	4.80	4.23	4.08	+ 0.15	3.54	0.881	0.850	8.45	8.60
4	7.0	5.30	4.55	4.15	+ 0.40	8.80	0.858	0.783	8.50	8.75
5	10.0	3.60	3.30	3.10	+ 0.20	6.05	0.917	0.861	8.50	8.75
6	5.0	4.33	4.61	4.47	+ 0.14	3.05	1.065	1.032	8.65	8.80
7	10.0	2.74	2.23	2.13	+ 0.10	4.50	0.814	0.777	8.00	8.25
8	4.0	1.75	1.78	1.56	+ 0.22	12.35	1.017	0.891	9.20	9.35
9	10.5	2.35	2.30	2.17	+ 0.13	5.65	0.979	0.923	8.90	9.05
10	3.00	5.10	5.85	5.40	+ 0.45	7.70	1.470	1.059	8.70	8.80
11	4.50	3.05	2.77	2.59	+ 0.18	6.50	0.908	0.849	8.65	8.80
12	5.50	2.90	2.75	2.51	+ 0.24	8.72	0.948	0.865	8.50	8.72
13	2.80	4.75	4.78	4.68	+ 0.10	2.10	1.006	0.985	8.75	8.85
14	6.00	5.35	4.83	4.50	+ 0.33	7.33	0.903	0.841	8.65	8.85
15	7.00	4.50	5.42	4.93	+ 0.49	9.02	1.204	1.095	8.45	8.65
16	3.50	4.79	5.73	5.26	+ 0.47	9.15	1.196	1.098	8.90	9.05
17	6.00	5.40	5.23	5.02	+ 0.21	4.03	0.968	0.929	8.80	8.90
18	6.50	3.52	3.78	3.64	+ 0.14	3.70	1.074	1.034	8.55	8.75
19	7.00	3.95	2.85	2.75	+ 0.10	3.52	0.722	0.696	8.60	8.75
20	6.00	3.80	3.80	3.70	+ 0.10	2.64	1.000	0.974	8.80	8.90
21	4.00	4.45	4.31	4.11	+ 0.20	5.86	0.968	0.924	8.65	8.75
22	5.00	4.40	4.55	4.34	+ 0.21	4.61	1.034	0.986	8.75	8.90
23	8.00	2.40	2.15	1.98	+ 0.17	7.90	0.896	0.825	8.70	8.90

NOTES 1 All resistivity values are corrected to a temperature base of 80° F

2 Ave $\frac{RmfH - RmfL}{RmfH} \times 100 = 6.2\%$

3 Ave $\frac{RmfH}{Rm} = 0.96$

4 Ave $\frac{RmfL}{Rm} = 0.873$

LEGEND

) emulsions broke down

difference in the electrical resistivity of high and low pressure filtrates cannot be explained easily and simply. It is, however, obvious that during high-pressure filtration some conducting ions are retained either in the mud or in the mud cake. This retention of conducting ions effects an increase in the resistivity of the high-pressure filtrate.

It has already been shown in Fig. 9 that emulsifiers added with oil to field muds tend to bring down the resistivity of the muds. The two main constituents of commercial emulsifiers are: sodium hydroxide and an organic material.

With some commercial emulsifiers, such as, "Carbonox", caustic soda is added with the carbonox. In others, such as "Emulsite" and "Speedy Drill", caustic soda is contained in the product.

Two series of tests were planned to investigate the effect of the organic constituent of the emulsifier. In the first series the effect of Carbonox, with and without caustic soda, on the resistivity of distilled water solutions of various concentrations were tried. The amount of caustic in a distilled water solution of Emulsite was found by titration with standarized hydrochloric acid. The results of this series of tests are contained in Table 8.

Table 8 --Effects of the Main Constituents of Emulsifiers on the Resistivity of Distilled Water

Caustic Soda grams	Carbonox grams	Emulsite grams	Distilled Water cc.	pH Value	Resistivity (ohm-meters) @ 72° F.
----	----	--	1000	----	Above 100
----	4.0	--	"	----	49.00
----	6.0	--	"	----	28.3
----	8.0	--	"	----	19.80
----	10.0	--	"	----	17.10
----	12.00	--	"	----	15.20
0.420	----	--	1000	11.80	4.60
0.420	4.0	--	"	11.20	9.00
0.420	8.0	--	"	9.25	15.55
0.420	12.0	--	"	8.15	13.50
*0.410	----	2	1000	9.15	15.00
----	----	4	"	10.00	8.20
----	----	6	"	10.20	6.20
----	----	8	"	10.40	4.75
----	----	10	"	10.20	3.92
----	----	12	"	10.20	3.42

* Note: 2 grams of emulsite per 1000 cc. distilled water contained 0.410 grams of caustic soda

It is interesting to note that up to a certain point, an increasing amount of Carbonox added to .OIN̄ Caustic Soda solution increased its resistivity, whereas it decreased the resistivity of distilled water. There was a reversal in the resistivity of Caustic Soda solution when the concentration was increased from 10 grams to 12 grams per 1000 cc. of distilled water. The following explanation is offered.

When Carbonox is added to .OIN̄ Caustic Soda solution, some of the base (NaoH) is taken out of solution by the organic matter of the emulsifier. This causes an increase in the resistivity of the system and a decrease in its pH values (Table 8). This trend of the resistivity values continues till concentration of Carbonox in distilled water becomes a major factor in effecting a reduction in the resistivity of the system.

In the case of Emulsite, the resistivity of the distilled water continues to decrease with the continued addition of Emulsite since Caustic Soda is contained in the chemical composition of Emulsite. Titration of a solution of 2 grams of Emulsite in 1000 cc. of distilled water with standardized hydrochloric acid showed the presence of 0.410 grams of Caustic Soda in it. This should reduce the resistivity of distilled water to about 4.5 ohm meters at 72°F. Note, the resistivity of 2 grams of Emulsite solution in 1000 cc. of distilled water

is 15.0 ohm-meters at 72°F. The same explanation, as used for Carbonox, can be given for the increased resistivity of Emulsite solution.

These experiments show that both Caustic Soda and the organic material of the emulsifiers are conducting. Also, Caustic Soda contains ions which are more conducting than the organic matter of the emulsifier. A high-pressure filtrate is lighter in color than that collected at a lower filtration pressure. This suggests a lower concentration of organic matter than the low-pressure filtrate of the same mud. Since pH of high-pressure filtrate is consistantly lower than that of the low-pressure filtrate from the same mud, further evidence is given to support the thought that the ionic content of the two types of filtration are different and that a high-pressure filtrate has less Caustic Soda ions than the low-pressure filtrate of the same mud. A generally lower resistivity of high-pressure filter cake suggests the probability of the loss of these conducting ions in high-pressure filter cake. This loss can probably be caused either by the entrapment of these ions in the compacted pores of the high-pressure filter cake or by their adsorption on the cake surface.

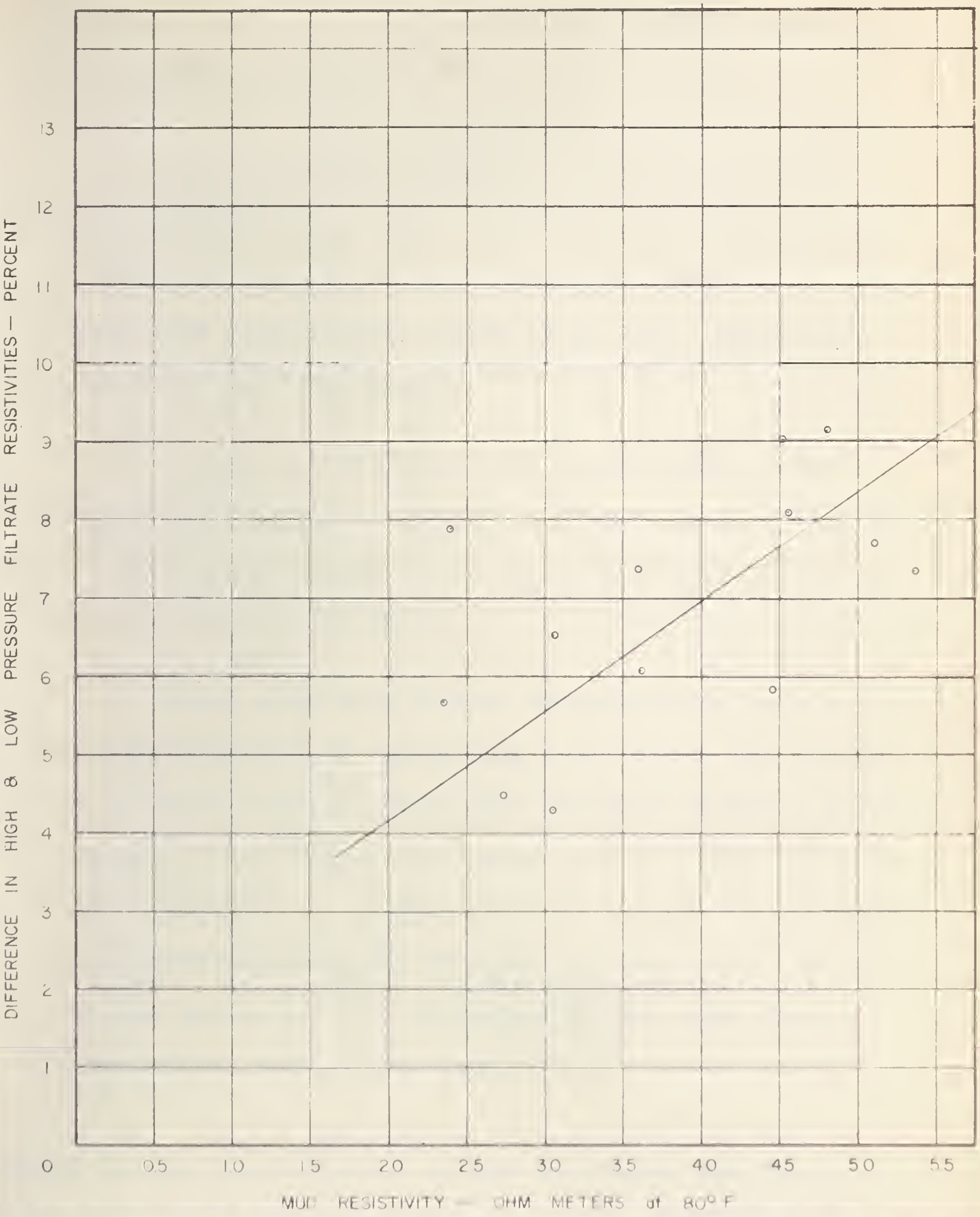

FIG 15, CHANGE IN THE DIFFERENCE BETWEEN HIGH & LOW PRESSURE FILTRATE RESISTIVITIES WITH MUD RESISTIVITY FOR PEMBINA OIL-EMULSION DRILLING FLUIDS

Difference in High and Low-Pressure Filtration Resistivities with Mud Resistivity

The difference between high and low-pressure filtrate resistivities seems to depend on the original resistivity of the mud. This difference tends to be high for muds with high resistivities (Fig. 15). Exceptions to this behaviour are present.

If the oil-emulsion muds "broke down" during high-pressure and high-temperature filtration the difference between the resistivities of the high and low-pressure filtrates was small.

Since muds with higher resistivities have a lower concentration of conducting ions within the liquid phase, a small loss of these ions probably causes a greater difference between high and low-pressure filtrate resistivities. Addition of sodium chloride to the mud decreases the difference appreciably as shown in Table 10. Scattering of the points of Fig. 15 suggests that more than one variable affect this difference.

Total Solids Concentration of Mud Filtrates and Their Resistivities

Table 9 gives data on the variation of filtrate resistivity with total solids concentration for Pembina

Table 9 -- Variation of Filtrate Resistivity With Total Solid Concentration for Pembina Oil Emulsion Drilling Fluid Filtrates

Field Sample #	Volume of Filtrate Evaporated cc.	Weight of Filtrate Evaporated grams	Weight of Solids Remaining grams	Solid Concentration per 2.00 grams of the filtrate grams	Solid Concentrate P.P.M.	Resistivity ohm-meters @ 81° F.
#13 HP	2.000	1.9753	0.0042	0.004250	212.5	4.78
#14 HP	2.000	2.0090	0.0034	0.003380	167.0	4.83
#15 HP	2.000	1.9954	0.0021	0.002106	105.3	5.42
#16 HP	2.000	1.9944	0.0016	0.001604	80.4	5.73
#17 HP	2.000	1.9993	0.0023	0.002302	115.1	5.23
#18 HP	2.000	1.9953	0.0053	0.005310	265.5	3.78
#18 LP	2.000	2.0182	0.0055	0.00542	271.0	3.64
#19 HP	2.000	1.99575	------	--------	-----	----
#19 LP	2.000	1.99910	0.0065	0.00650	325.0	2.75
#20 HP	2.000	2.0033	0.0453	0.00448	224.0	3.80
#21 HP	2.000	1.9877	0.0040	0.00402	201.0	4.51
#21 LP	2.000	1.9979	0.0043	0.00432	216.0	4.11
#22 HP	2.000	1.4908	0.0032	0.00322	161.0	4.55
#22 LP	2.000	1.9952	5.0034	0.00342	171.0	4.34
#23 HP	2.000	2.0034	0.0076	0.00758	379.0	2.15
#23 LP	2.000	1.9880	0.0079	0.00794	397.0	1.98

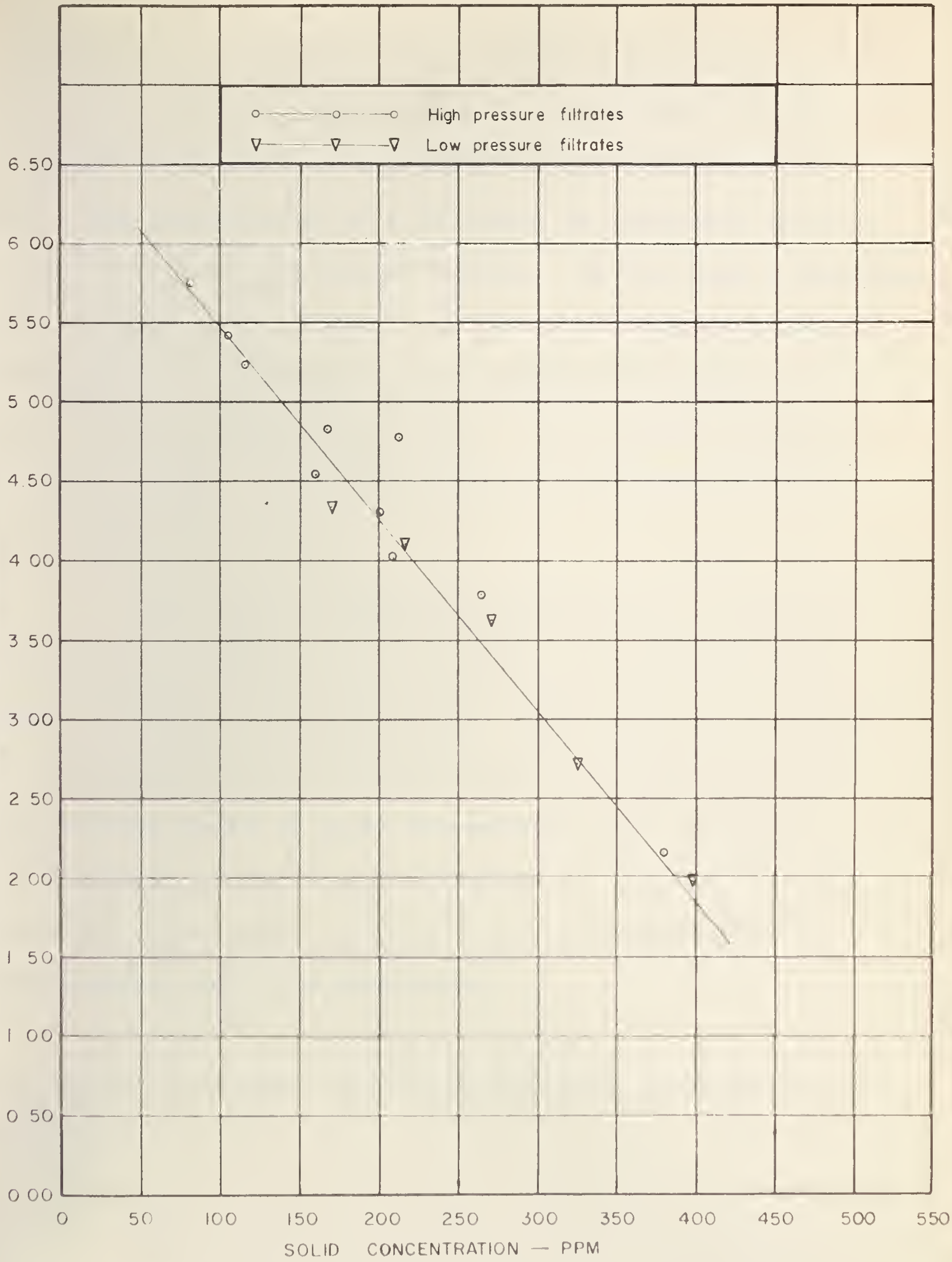

FIG 16, VARIATION OF FILTRATE RESISTIVITY WITH TOTAL SOLIDS CONCENTRATION FOR PEMBINA OIL EMULSION DRILLING FLUIDS.

Oil-emulsion drilling fluid filtrates. The plot of these data, Fig. 16, suggests a linear relationship between the filtrate resistivities and their solids concentration. Also, the resistivity of a filtrate is inversely proportional to its solids concentration. On the last 5 Samples, where solids concentration was obtained both on high and low-pressure filtrates, a high-pressure filtrate had a lower solid concentration than a low-pressure filtrate of the same mud. This explains the difference between the resistivity values.

The solid concentration resistivity relationship for oil-emulsion mud filtrates is different than that for sodium chloride brines. For instance, a sodium chloride solution of 1500 PPM solid concentration has a resistivity value of 3.30 ohm-meters @ $80^{o}F$ whereas a mud filtrate of solid concentration of only 300 PPm has the same resistivity. This fact is not explained by experimental data now available.

Variation of Filtrate Resistivities with Additive Concentration

The effect on the resistivity of filtrate by the addition of sodium chloride to mud was investigated in a series of tests on a field sample of Pembina oil-emulsion drilling fluids. The results are contained in Table 10 and the resistivity-solid concentration data

TABLE 10, VARIATION OF CHEMICAL, PHYSICAL AND ELECTRICAL PROPERTIES OF A PEMBINA OIL-EMULSION DRILLING FLUID SAMPLE 25 (16-2-48-9W5 WITH ADDITIVE CONCENTRATION.

Sample No	Oil percent	pH of the mud	Rm Ohm meters	Rmf		Rmc		pH values		Solid concentration PPM		Filtration Characteristics				REMARKS
				RmfH	RmfL	RmcH	RmcL	H.P. Filtrate	L.P. Filtrate	H.P. Filtrate	LP Filtrate	H.P. Filtrate		L.P. Filtrate		
												1 hr loss	15 hr. loss	1 hr. loss	15 hr. loss	
25	5.0	8.50	4.30	4.02	3.86	3.50	3.65	8.50	8.70	185	215	3.30	10.80	2.50	8.30	Origional sample mud
25A	5.0	8.55	3.74	3.22	3.13	3.75	3.85	8.45	8.55	210	225	2.90	10.00	2.90	8.70	200 PPM NaCl added to mud
25B	5.0	8.40	3.06	2.54	2.44	3.85	3.90	8.42	8.48	260	280	4.90	15.20	2.80	8.35	600 " " " " "
25C	5.0	8.45	2.80	2.21	2.21	3.90	3.95	8.40	8.45	290	300	5.20	17.70	3.50	8.70	800 " " " " "
25D	5.0	8.50	2.45	2.10	2.10	3.45	3.45	8.50	8.55	340	345	2.60	11.55	3.40	10.70	1200 " " " " "
25E	5.0	8.45	2.10	1.37	1.37	2.95	2.95	8.45	8.40	430	435	5.80	21.50	2.60	7.95	2000 " " " " "
25F	15.0	9.05	3.40	3.00	2.90	4.40	4.60	8.70	8.80	295	320	3.40	10.00	2.30	5.60	10% oil and 2.0 gms of emulsite added. Emulsion breakdown occured

NOTE All values have been corrected to a temperoture base of 80° F

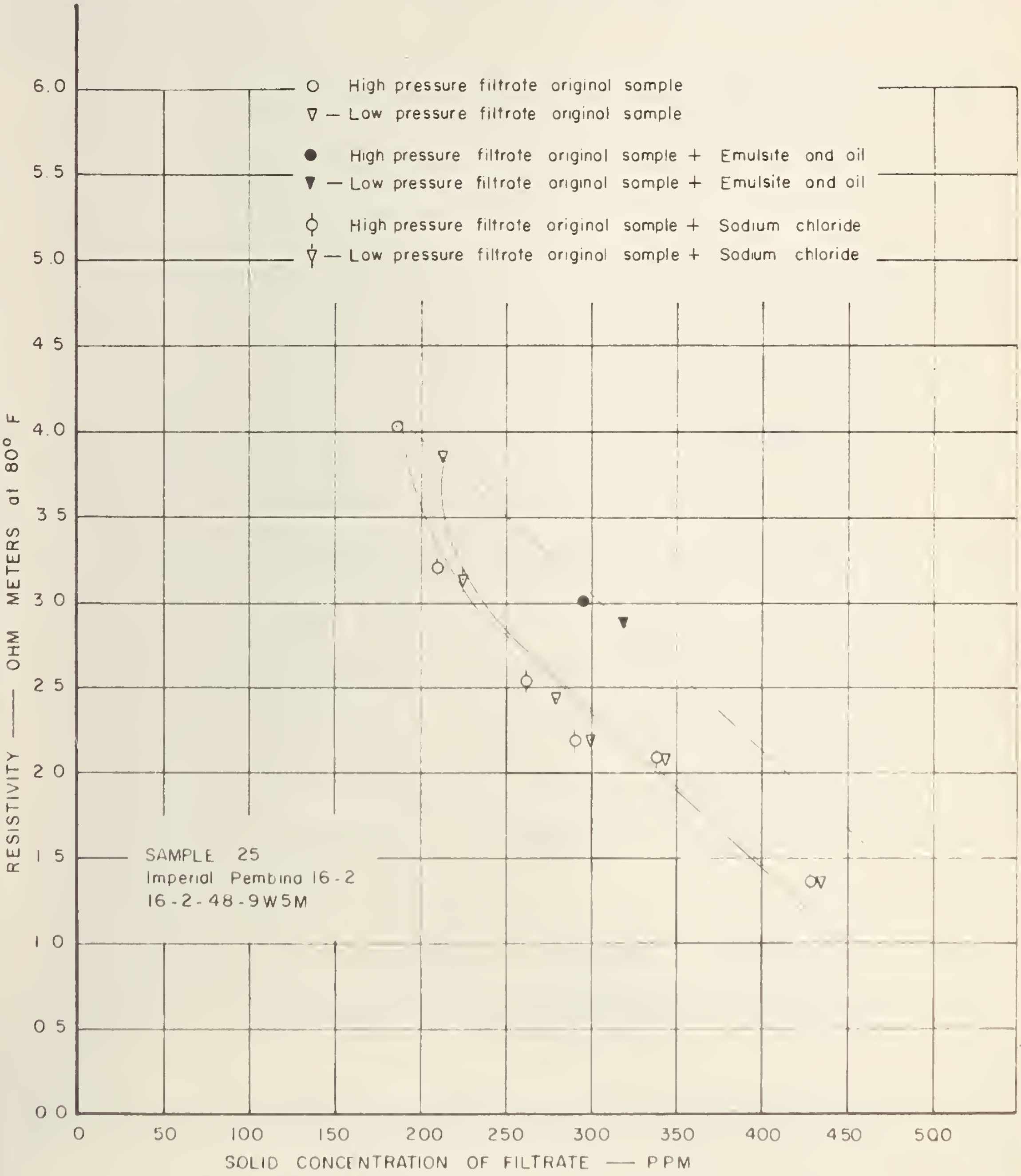

FIG 17, VARIATION OF RESISTIVITY OF HIGH AND LOW PRESSURE FILTRATES WITH ADDITIVE CONCENTRATION FOR A PEMBINA OIL EMULSION DRILLING FLUID

are shown in Fig. 17.

The observations of interest based on these data are:

1. The resistivity of the mud and its filtrate were appreciably reduced by the addition of sodium chloride.
2. The difference in the high and low-pressure filtrate resistivities were gradually reduced to zero when a certain concentration of sodium chloride in the original mud was reached. As mentioned earlier, if an abundance of conducting ions are present in a mud system, there is little difference between solid concentration of the filtrates obtained at different filtration pressures.
3. The addition of sodium chloride tends to increase the filter-loss behaviour of the mud.
4. The addition of oil and an emulsifier tends to reduce the filter-loss of the mud.

The Ratio of Filtrate Resistivity to Mud Resistivity

Resistivity of an oil-emulsion mud filtrate is generally closely related to its mud resistivity. The filtrate resistivity is frequently less than that of the mud. Since oil content of an oil-emulsion mud is one of

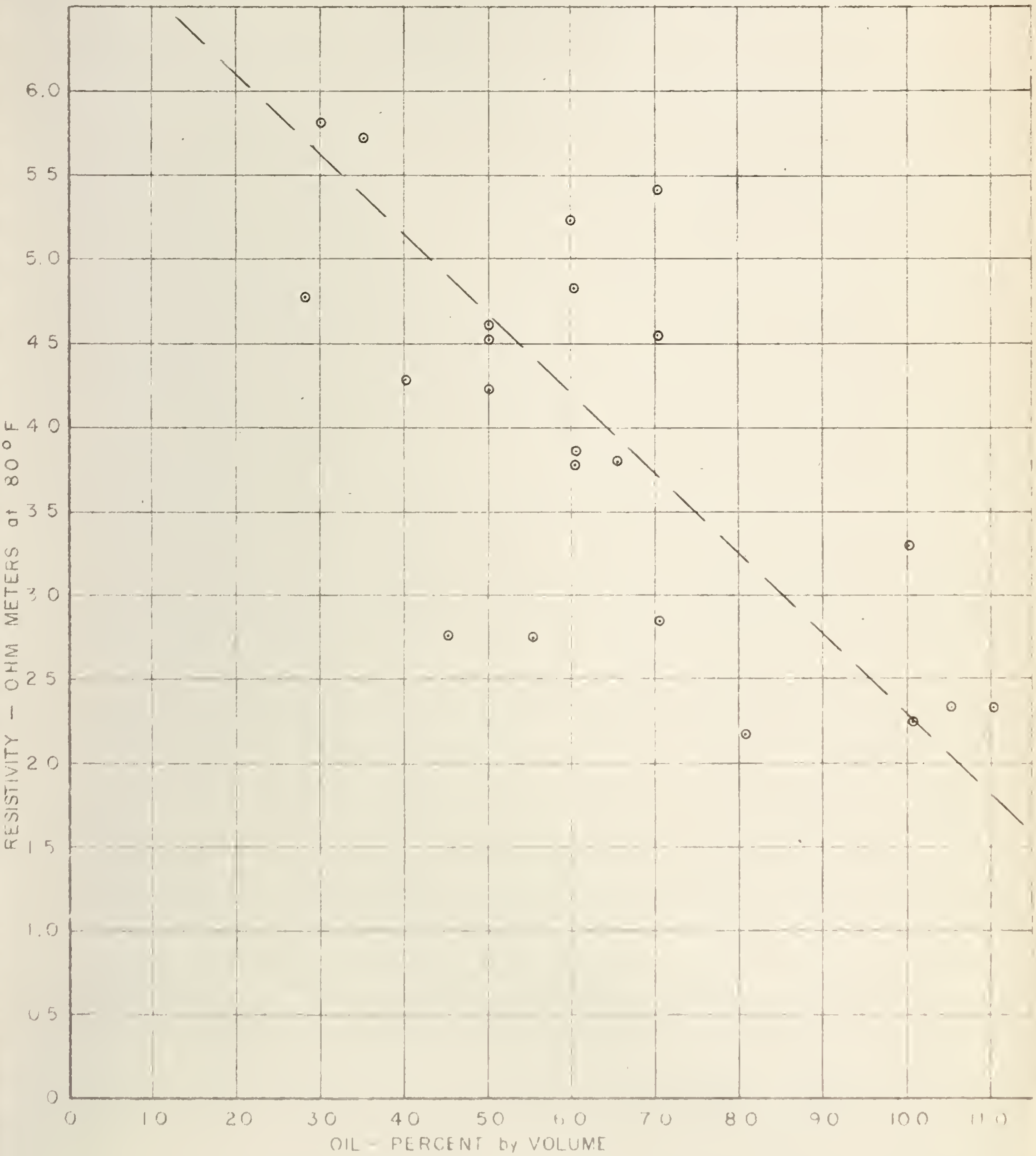

FIG. 18, RESISTIVITY TREND FOR HIGH-PRESSURE FILTRATES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS OF VARYING OIL CONTENT

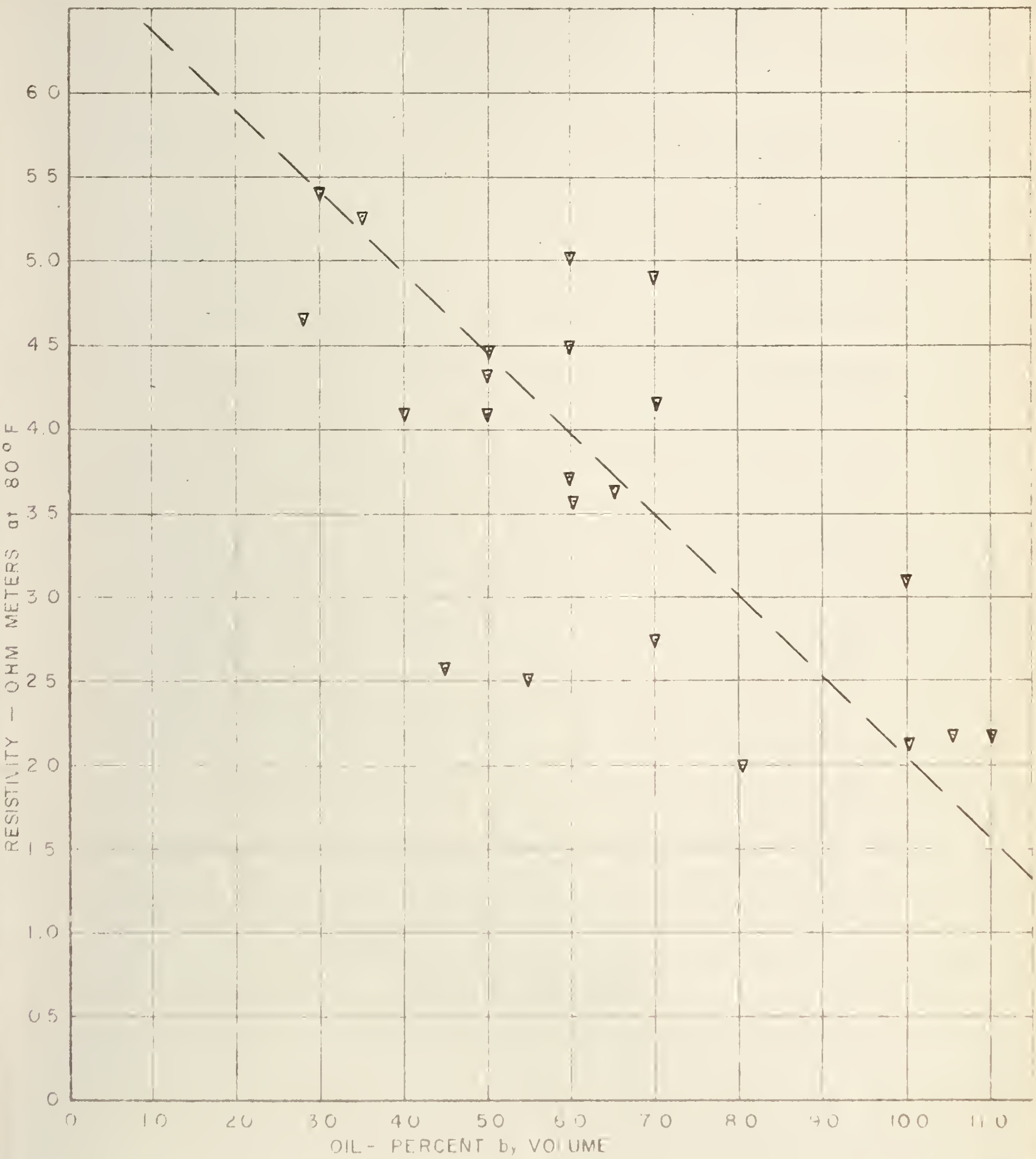

FIG. 19, RESISTIVITY TREND FOR LOW-PRESSURE FILTRATES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS OF VARYING OIL CONTENT

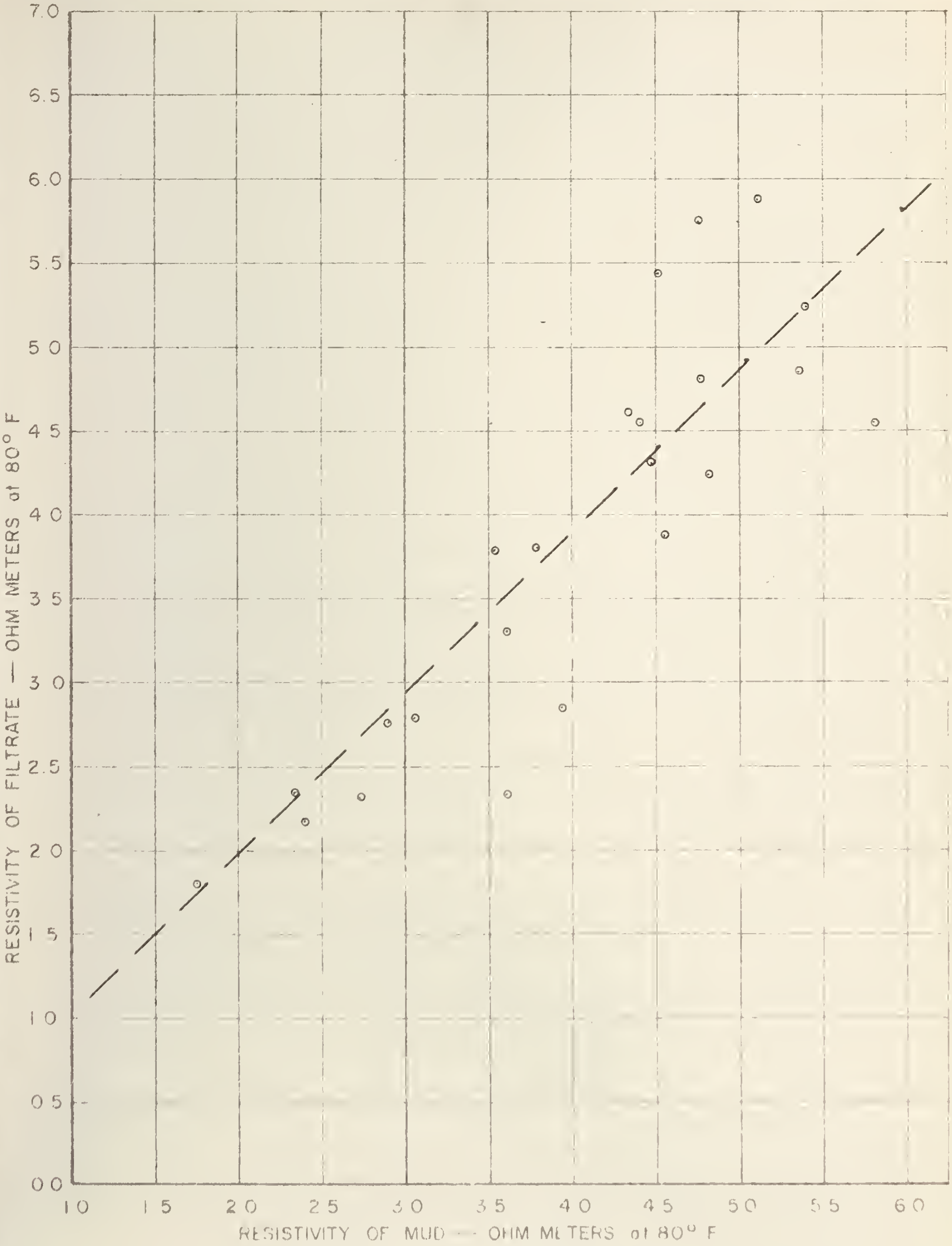

FIG. 20, VARIATION OF HIGH-PRESSURE FILTRATE RESISTIVITY WITH MUD RESISTIVITY FOR PEMBINA OIL-EMULSION DRILLING FLUIDS.

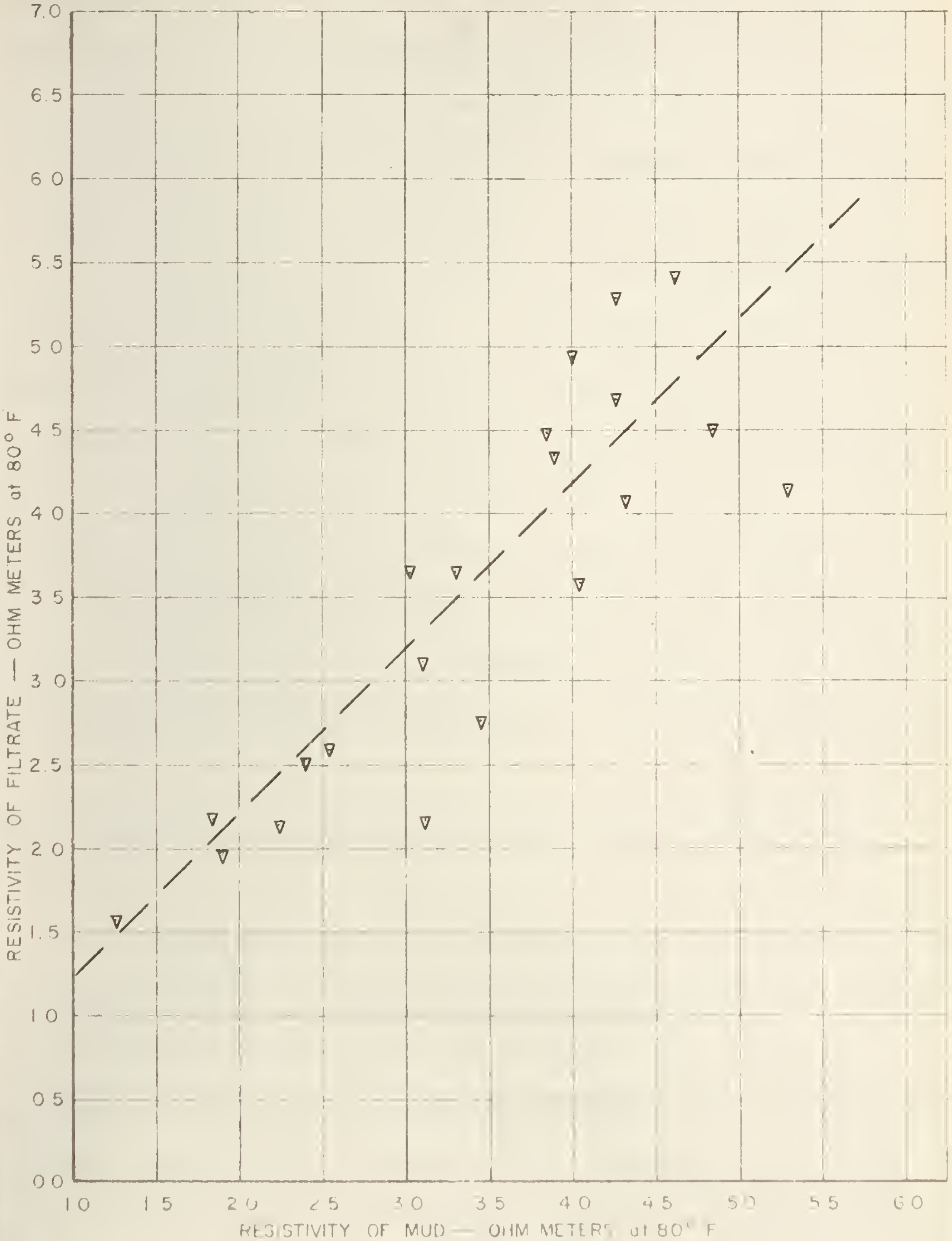

FIG. 21, VARIATION OF LOW-PRESSURE FILTRATE RESISTIVITY WITH MUD RESISTIVITY FOR PEMBINA OIL-EMULSION DRILLING FLUIDS.

the factors that influences its resistivity, a trend of the resistivities of high and low-pressure filtrates with oil content of the mud can be seen in Fig. 18 and Fig. 19. The average values of the ratio of filtrate resistivity to mud resistivity as obtained on 23 field samples is found to be about 0.969 in the case of high-pressure filtrates and 0.870 for those of low-pressure filtrates. Large deviations from these averages are sometimes encountered. In the case of high-pressure filtrates this range of variation is from 0.647 to 1.470, and 0.600 to 1.095 in the case of low-pressure filtrates (Table 7). Most of the values, however, remain close to the average values. Fig. 20 and Fig. 21 show the trend of high and low-pressure filtrate resistivities with mud resistivity.

The Ratio of Mud Cake Resistivity to Mud Resistivity

Resistivity of an oil-emulsion mud cake is also closely related to its mud resistivity and shows a trend with its oil content (Fig. 22 and Fig. 23). On the average mud cake resistivity was found to be slightly greater than its mud resistivity. In the case of high-pressure mud cake, this average ratio of mud cake resistivity to its mud resistivity is about 1.042 and about 1.1045 for those of low-pressure mud cakes. The average for the R_{mc}/R_m ratio was greater than for the comparable filtrate ratio data. For instance, the range of variation the factors that influences its resistivity, a trend of the resistivities of high and low-pressure filtrates with oil content of the mud can be seen in Fig. 18 and Fig. 19. The average values of the ratio of filtrate resistivity to mud resistivity as obtained on 23 field samples is found to be about 0.969 in the case of high-pressure filtrates and 0.870 for those of low-pressure filtrates. Large deviations from these averages are sometimes encountered. In the case of high-pressure filtrates this range of variation is from 0.547 to 1.470, and 0.606 to 1.095 in the case of low-pressure filtrates (Table 7). Most of the values, however, remain close to the average values. Fig. 20 and Fig. 21 show the trend of high and low-pressure filtrate resistivities with mud resistivity.

The Ratio of Mud Cake Resistivity to Mud Resistivity

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TABLE 11, COMPARISON OF ELECTRICAL CHARACTERISTICS OF FILTER CAKES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS AT DIFFERENT PRESSURES

FIELD SAMPLE No	OIL PERCENT	Rm at 80°F Ohmmeters	RmcH at 80°F Ohm meters	RmcL at 80°F Ohm meters	RmcH - RmcL Ohm meters	$\frac{\text{RmcH-RmcL}}{\text{RmcH}}$ x 100 Percent	$\frac{\text{RmcH}}{\text{Rm}}$	$\frac{\text{RmcL}}{\text{Rm}}$
1	11.0	3.60	3.99	4.30	− 0.31	− 7.75	1.108	1.194
2	6.0	4.55	3.80	3.90	− 0.10	− 2.63	0.835	0.857
3	5.0	4.80	3.80	3.90	− 0.10	− 2.63	0.792	0.813
4	7.0	5.30	4.00	4.25	− 0.25	− 6.25	0.755	0.802
5	10.0	3.60	3.50	3.725	− 0.225	− 6.42	0.972	1.033
6	5.0	4.33	4.05	3.70	+ 0.35	+ 9.75	0.935	0.854
7	10.0	2.74	3.40	3.80	− 0.40	− 11.75	1.241	1.387
8	4.0	1.75	2.75	2.60	+ 0.15	+ 5.45	1.571	1.486
9	10.5	2.35	4.10	4.80	− 0.70	− 17.05	1.745	2.040
10	3.0	5.10						
11	4.5	3.05	3.55	3.70	− 0.15	− 4.22	1.164	1.213
12	5.5	2.90	3.20	3.00	+ 0.20	+ 6.25	1.103	1.034
13	2.8	4.75	4.10	4.35	− 0.25	− 6.10	0.863	0.916
14	6.0	5.35						
15	7.0	4.50		4.55				1.071
16	3.50	4.79	3.70	4.05	− 0.35	− 9.45	0.772	0.845
17	6.0	5.40	4.70				0.870	
18	6.5	3.52	3.75	4.275	− 0.525	− 14.0	1.065	1.213
19	7.0	3.45	4.95	4.85	+ 0.10	+ 2.02	1.253	1.228
20	6.0	3.80	3.55	4.05	− 0.55	− 15.50	0.934	1.066
21	4.0	4.45	4.08	4.40	− 0.32	− 7.89	0.917	0.989
22	5.0	4.40	4.05	4.25	− 0.20	− 4.94	0.920	0.966
23	8.0	2.40	2.45	2.60	− 0.15	− 6.12	1.021	1.083

NOTES: 1. All resistivity values are corrected to a temperature base of 80° F.

2. Ave $\frac{\text{RmcH} - \text{RmcL}}{\text{RmcH}} \times 100 = -5.5\%$

3. Ave $\frac{\text{RmcH}}{\text{Rm}} = 1.042$

4. Ave $\frac{\text{RmcL}}{\text{Rm}} = 1.1045$

LEGEND

] emulsion broke down

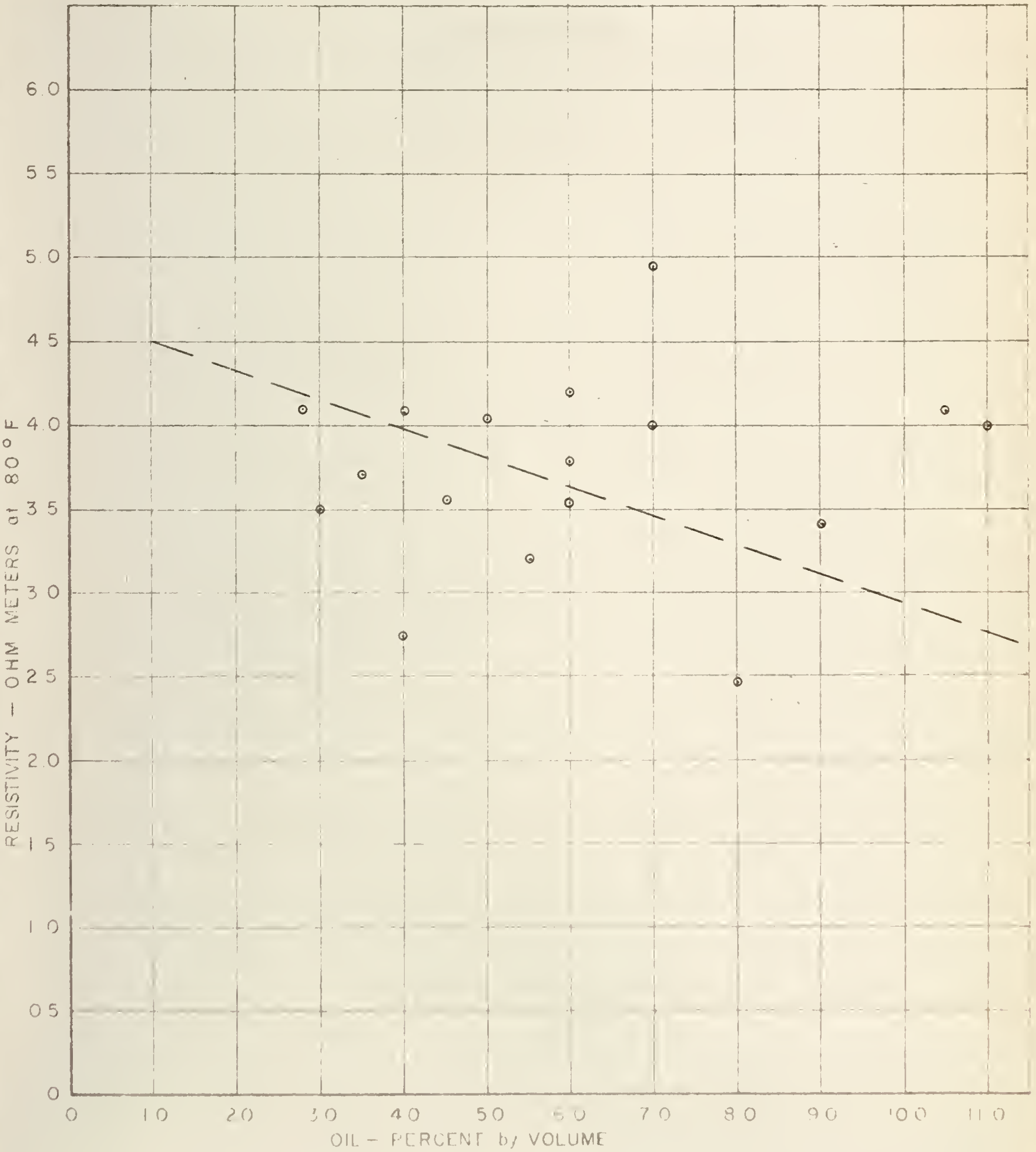


FIG. 22, RESISTIVITY TREND FOR HIGH-PRESSURE FILTER CAKES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS OF VARYING OIL CONTENT

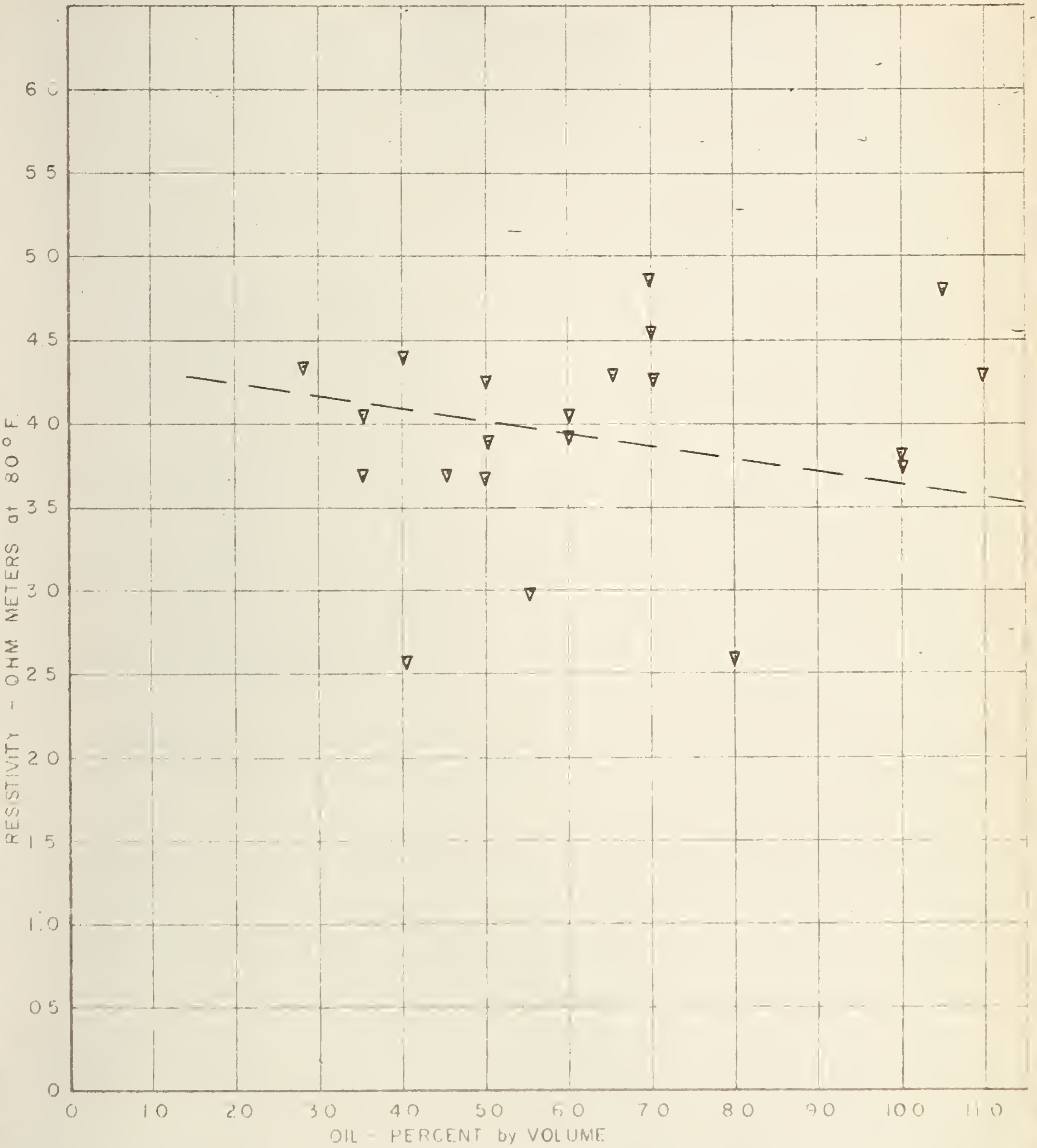


FIG. 23, RESISTIVITY TREND FOR LOW-PRESSURE FILTER CAKES OBTAINED FROM PEMBINA OIL-EMULSION DRILLING FLUIDS OF VARYING OIL CONTENT.

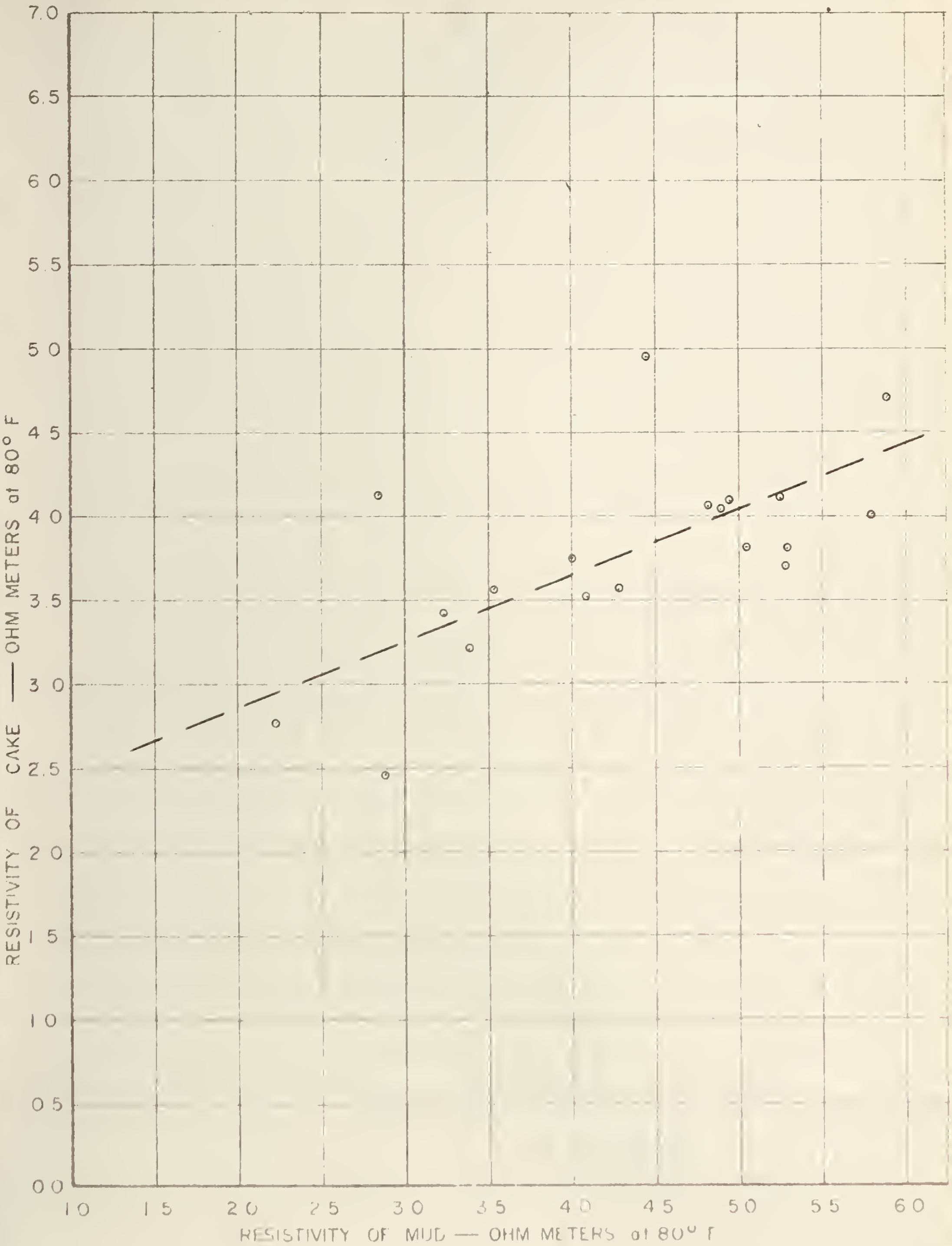


FIG. 24, VARIATION OF HIGH-PRESSURE FILTER CAKE RESISTIVITY WITH MUD RESISTIVITY FOR PEMBINA OIL-EMULSION DRILLING FLUIDS.

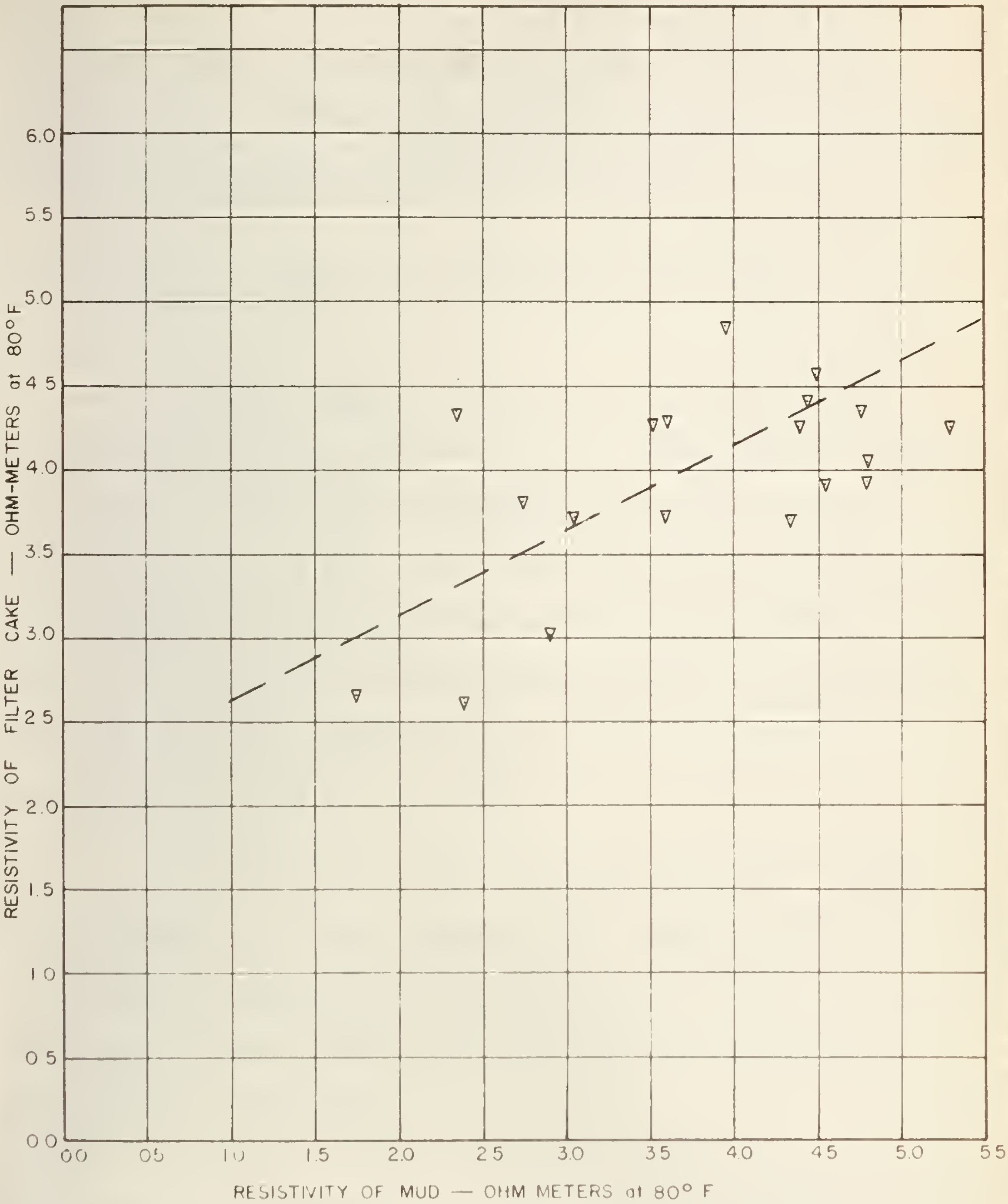


FIG 25, VARIATION OF LOW-PRESSURE FILTER CAKE RESISTIVITY WITH MUD RESISTIVITY FOR PEMBINA OIL-EMULSION DRILLING FLUIDS

on high-pressure mud cake was from 0.775 to 1.745 and 0.802 to 2.040 in the case of low-pressure mud cakes. Fig. 24 and Fig. 25 show the trend of high and low-pressure mud cake resistivity with mud resistivity.

Resistivities of High and Low-Pressure Mud Cakes

Usually, high-pressure mud cake had a lower resistivity than the low-pressure mud cake from the same mud sample. The average difference in their resistivities is about - 5.5%. Large deviations occur from this mean average. For instance a maximum negative difference of 17.05% and a maximum positive difference of 9.75 are also present. However, most of the differences are around the average values (Table 11).

The generally lower resistivity range of the high-pressure mud cakes suggests that more of the conducting ions initially within the mud are retained by the high pressure filter cake than by the low-pressure cake during filtration.

Filtration Characteristics of the Drilling Fluids

Table A-1 compares the filter-loss behaviour of the samples of Pembina oil-emulsion drilling fluids at high (1000 P.S.I.G.) and low (100 P.S.I.G.) pressures

and temperatures. In the case of the first seven field samples, room temperature was maintained during high and low-pressure filtration. In the rest of the other samples a temperature of about 115°F was maintained during high-pressure filtration. The values of Table A-1 have been obtained by plotting Filter-loss against Time as shown by Fig. A-2 and Fig. A-3. The following table presents a summary of the filtration data:

Time	Ave. F.L. @ 100 psi & @ 80°F	Ave. F.L. @ 1000 psi & @ 80°F	Ave. F.L. @ 1000 psi & 115°F	% Difference	
7½ min. loss	0.924	1.06	---	+ 14.7	
30 min. loss	1.50	1.60	---	+ 6.6	*
1 hr. loss	1.82	2.22	---	+ 22.0	
15 hr. loss	6.76	8.60	---	+ 27.2	
7½ min. loss	0.80	---	1.20	+ 50.0	
30 min. loss	1.73	---	2.75	+ 59.0	**
1 hr. loss	2.19	---	3.89	+ 77.5	
15 hr. loss	7.07	---	12.00	+ 69.7	

Notes: * Average of first seven field samples.

** Average of last 16 field samples.

The results of the above table clearly show the effect of high-temperature and high-pressure on the filtration rates of the drilling fluids. High temperature particularly seems to have great effect on the filtration

rate of oil-emulsion drilling fluids.

In some samples "break-down" of the emulsion occurred during high-pressure and high-temperature filtration. This resulted in the appearance of an oil phase at the top of the high-pressure filtrates. Clearer filtrates were obtained from the same muds at a lower pressure and room temperature.

No correlation between the filtration rates and the electrical properties of oil-emulsion muds could be obtained from the available data. However, results supported the work of Shremp & Johnson and reemphasized the importance of determining the filter loss characteristics of oil-emulsion drilling fluids under well-bore filtration temperatures and pressures.

CONCLUSIONS

Consideration of the data obtained from the study of the physical and electrical characteristics of 25 samples of Pembina oil-emulsion drilling fluids leads to the following conclusions:

1. The resistivity of an oil-emulsion mud is lowered appreciably by increasing its bentonite or emulsifier content.
2. The addition of oil to an oil-emulsion mud tends to increase its resistivity. This effect, however, is only slight in the presence of bentonite, emulsifier, or other conducting solids.
3. A temperature increase from 80°F to 160°F reduces the resistivity of mud to about 50% of that at 80°F.
4. For temperature corrections, Arps' original formula $\frac{(R_w)t_2}{(R_w)t_1} = \frac{t_1 + 7}{t_2 + 7}$ gives resistivities which are higher than the experimental values of oil-emulsion mud (or their filtrates) at temperature above 80°F.
5. The adjusted form $\frac{(R_m)t_2}{(R_m)t_1} = t_1/t_2$ gives values closer to the experimental values for

temperatures up to 160°F.

6. If the resistivities of oil-emulsion muds or its filtrate are to be corrected for temperature above 160°F, the adjusted form $\frac{(R_m)_{t_2}}{(R_m)_{t_1}} = \frac{t_1 + 2}{t_2 + 2}$ is likely to give better results.
7. A pressure increase (up to 800 P.S.I.G.) seems to have little effect on the resistivity of oil-emulsion mud.
8. The resistivities of mud filtrates and filter cakes are usually related to their base mud resistivities. Large deviations in the relation of resistivity of mud filtrate or filter cake to the resistivity of the base mud are present.
9. Filtration pressure affects the electrical resistivities of mud filtrates and filter cakes. A high-pressure filtrate has invariably a higher resistivity than a low-pressure filtrate obtained from the same mud. On the other hand, a high-pressure filter cake usually has a lower resistivity than a low-pressure filter cake collected from the same mud.
10. To obtain a precise explanation for the resistivity phenomenon of the mud filtrates

and filter cakes, a very careful and detailed chemical analysis of the filtrates and filter cakes is desirable.

11. Both high filtration pressure and high filtration temperature tend to increase the filtration rate of oil-emulsion muds.
12. Both high filtration pressure and high filtration temperature tend to break down the emulsion of some poor muds.
13. Resistivity of an oil-emulsion mud or its filtrate is reduced appreciably by the addition of sodium chloride.
14. Addition of sodium chloride to an oil-emulsion mud also tends to increase its filter loss.
15. For accurate determination of the electrical properties of an oil-emulsion mud filtrate or its filter cake, these measurements should be made on actual field sample of mud at a filtration pressure and a temperature which closely simulate the bottom-hole conditions. The surface measurements of their resistivities should then be corrected for the temperature existing at the bore-hole by any one of the adjusted forms of Arps' original approximation formula.

TABLE A-1 PHYSICAL AND ELECTRICAL CHARACTERISTICS OF FIELD SAMPLES OF PEMBINA OIL-EMULSION DRILLING FLUIDS

Field Sample	Well Name	Well Location	Composition Analysis				THE PHYSICAL CHARACTERISTICS OF OIL-EMULSION MUDS												pH VALUES			THE ELECTRICAL CHARACTERISTICS OF OIL-EMULSION MUDS					
			Water Content %	Oil Content %	Solid Content		Fonn Viscosity at 600 rpm (cps)	Density lbs /U S gal	Gel Strength		Filtration Characteristics											Resistivity (Ohm - meters) at "t" Degrees Farenheit					
					Total %	Sand %			0 - MIN gm	10 - MIN gm.	HIGH PRESSURE FILTRATE				LOW PRESSURE FILTRATE				MUD	H. P. Filtrate	L.P. Filtrote	MUD		FILTRATE		MUD CAKE	
											7 1/2 min loss cc	30 min. loss cc	1 hr loss cc	15 hr loss cc	7 1/2 min loss cc	30 min loss cc	1 hr loss cc	15 hr loss cc				BY SWSCO MUD CUP	BY SWSCO FILTRATE TUBE	High Pressure	Low Pressure	High Pressure	Low Pressure
	Soc-Seab Pem 1-16	16-1-48-8 W5	71 0	11 0	18 0	—	88,20	11.3	15 0	144.0	1.30	1 90	2 45	7 90	1 12	1 68	1 92	5 45	8.00	9 40	9 90	3 38 at 74°	4 50 at 69°	2 83 at 72°	2 60 at 72°	4 15 at 76°	4 58 at 73°
2	Soc-Seab 8 C. 35-6	6-35-47-7 W5	71 0	6 0	23 0	—	70 0	11 8	35 78	250 0	1.32	1 97	2.90	10.50	1 28	1 73	2 25	6 90	8 20	8 45	8 70	5 15 at 70°	4 75 at 79°	4 10 at 77°	3 80 at 77°	3 90 at 77°	4 00 at 77°
3	Stan -H 8 Pem Crw F-29	2-19-47-8 W5	76 0	5 0	19 0	—	72 0	11 28	15 5	155 0	1.24	2 02	2.70	9 50	0.95	1.47	1 90	6 25	8 50	8 45	8 60	5 10 at 74 5°	5 20 at 78°	4 90 at 74°	4 68 at 74°	4 10 at 74°	4 20 at 74°
4	Stan -H 8 Pem Crw F-43	10-20-47-8 W5	77.0	7 0	16.0	—	64 0	11.05	35.0	184.0	1.15	1 85	2.70	10.25	1 02	1 57	2 10	7 80	8 45	8 50	8 75	5 80 at 71°	6 20 at 71°	4 95 at 80°	4 75 at 73°	4 10 at 77°	4 70 at 71°
5	Soc-Seab Pem 2-10	10-2-48-8 W5	70 0	10 0	20 0	—	98 0	11 20	2 7	30 0	0.75	1 42	1 80	6 60	0 95	1 58	1 70	5 30	8 30	8.50	8 75	3.80 at 76°	4 30 at 76°	3 62 at 81°	3 40 at 81°	3 50 at 80°	3 725 at 80°
6	Stan -H B Pem Crw A-35	12-15-48-9 W5	79 0	5 0	16.0	—	134.0	10 85	57 0	159.0	—	0.75	1.35	8.20	0.75	1.45	1 60	5 80	8.25	8 65	8 80	4 55 at 75°	4 45 at 83°	5 00 at 79°	4 65 at 82°	4 20 at 77°	3 85 at 77°
7	C-t Ser et al Easyford 6-5	6-5-50-6 W5	73 0	10 0	17 0	—	97 0	11 60	5 0	97 0	0 60	1.32	1.80	7 30	0.40	1.05	1.25	5.60	7.50	8.00	8.25	3.10 at 74°	3.35 at 76°	2 65 at 74°	2 75 at 69°	3 975 at 66°	4 50 at 66°
8	Cat Std Cyn N E 4-25	4-25-50-12 W5	84.0	4.0	12 0	2 9	23.0	10 20	2 70	17 7	1.30	3 0	4 15	16.55	1 0	1 80	2.50	8.0	9.80	9 20	9 35	1.75 at 85°	2.30 at 80°	2 20 at 85°	1 80 at 85°	2.60 at 85°	2 40 at 65°
9	Cal Std 8-11		73.0	10 5	16 5	2.0	26.0	10.45	2.60	6.70	0.80	1 41	1 85	6.90	—	0.41	0.95	3.85	9.40	8 90	9.05	2.41 at 81°	2 80 at 82°	2.60 at 80°	2 45 at 80°	4 10 at 80°	4 80 at 80°
10	M.O -Seab 8C 35-14	14-35-47-7 W5	82 0	3 0	15 0	nil	13 0	10.20	0.20	1.0	2.80	6.05	9.0	—	—	0 70	1 20	—	8 40	8 70	8.80	5 10 at 82°	5 40 at 80°	6.20 at 80°	5 80 at 78°	— —	— —
11	M.O - Seab V G 11		76 5	4 5	19.0	2 6	35.0	11.40	3.20	39.0	1 30	3 30	5 0	—	0.50	1 20	1 40	—	8.50	8.65	8.80	3 05 at 80°	3.30 at 80°	3.00 at 80°	2 80 at 80°	3.55 at 80°	3.70 at 80°
12	M O -Seab V G 22-8	8-22-48-7 W5	75 0	5 5	20 0	0 4	44 0	12.2	3 0	5.70	—	0 40	0 55	6 50	0 25	0 65	0.80	3.30	8 75	8.50	8.72	2 40 at 94°	2 90 at 84°	3.05 at 76°	2 80 at 76°	3 45 at 76°	3 28 at 76°
13	Stan 8-30	16-33-48-9 W5	82 0	2 8	15 2	2 5	50 0	11 0	6 70	145 7	1 09	2 20	3 40	16.25	0 70	1 40	2 10	9 75	8 00	8.70	8 85	4 40 at 86°	5.00 at 81°	5.10 at 80°	5.00 at 80°	4 10 at 80°	4 35 at 80°
14	Stan E-32	16-32-47-10 W5	75 0	6 0	19 0	1 0	28 5	10 60	5 70	45 78	0 50	1 55	2 50	13 90	1.10	1 80	2 45	9 30	7.80	8 65	8.85	5.15 at 85°	5.70 at 80°	4.95 at 82°	4 85 at 79°	— —	— —
15	M O -Seab D V 7-16	16-7-49-7 W5	69 0	6.0	25 0	1 5	49 0	11 40	3 70	57 5	1 20	2.8	3 90	11 50	0 80	2 00	2 65	6 80	7 95	8.45	8.65	4 50 at 80°	4 90 at 80°	5 80 at 81°	5.30 at 81°	— —	4 50 at 60°
16	M O -Seab N Pem 7-2	2-7-49-8 W5	82 0	3.5	14 5	0 3	16 0	10 65	0 0	2 0	2 30	4 90	7 20		1 50	2 95	3 30	7 90	8 60	8 90	9 05	5 00 at 77°	5 10 at 80°	6.10 at 80°	5 60 at 80°	3 70 at 80°	4 05 at 80°
7	M O -Seab Pem 25-12	12-25-48-8 W5	71 0	6 0	23 0	1 0	35 0	10 65	2 0	14.7	1 40	3.95	6 0	17 50	0 20	1 46	2 15	5 00	8.55	8 80	8.90	5.30 at 80°	5.55 at 83°	5 00 at 80°	5 40 at 80°	4 70 at 80°	— —
8	M O -Seab Pem 6-2	2-6-48-8 W5	75 5	6 5	19.0	1 9	26 0	11 30	2 0	25 78	—	1 00	1.70	10 00	1 30	2.35	2 60	7.55	8 25	8.55	8 77	3 40 at 62°	4 05 at 76°	4 10 at 80°	3 69 at 80°	3 75 at 80°	4 275 at 80°
19	M O.-Seab N Pem 6-2	2-6-49-8 W5	70.0	7 0	23 0	2 0	28 0	11 05	2.0	34 0	1 60	3.52	4.60	13 65	1 25	2 50	3 10	8 20	8 70	8 60	8 75	3.80 at 63°	4.10 at 82°	3.10 at 80°	3 00 at 80°	4.95 at 80°	4 85 at 60°
20	M O -Seab N Pem 7-2	2-7-49-8 W5	71 0	6 0	23 0	1 4	44 0	10 75	2 7	28 0	0 85	1 80	2 60	11 40	0 85	1 70	1 70	5 50	8.55	8.80	8 90	3 55 at 87°	3 80 at 84°	4 10 at 78°	4 00 at 78°	3 50 at 61°	4 00 at 8 °
21	Stan -H B Rat Cr 13-1	6-12-46-8 W5	78 0	4 0	18 0	1 5	20.0	11.05	0 0	2.50	1.80	2.90	3 75	12 50	1.25	1 25	2 46	7.75	8 65	8.65	8 75	4 10 at 86°	4 52 at 83°	4 50 at 80°	4 30 at 80°	4 08 at 80°	4 40 at 80°
22	M O -Seab V G 35-4	4-35-47-7 W5	71 0	5 0	24 0	1.8	58 0	11 10	4 0	41 7	1.60	3 80	4 50	13 50	1 00	2.50	3.0	8.50	8.60	8 75	8.90	4 18 at 86°	4.33 at 83°	5 15 at 81°	4 90 at 81°	4 05 at 80°	4 25 at 80°
23	—— ———	———	81 0	8.0	11 0	1 75	202 0	9 65	5.0	11 0	0 55	1 40	1 60	7 50	1 10	2 40	2.70	7 6	8.65	8.70	8 95	2 35 at 82°	2 65 at 80°	2 33 at 81°	2 15 at 81°	2 45 at 80°	2 46 at 80°

TABLE A-2 ELECTRICAL CHARACTERISTICS OF FIELD SAMPLES OF PEMBINA OIL-EMULSION DRILLING FLUIDS

All electrical resistivity values corrected to a temperature base of 80° F.

Field Sample	Oil %	Resistivity of Mud (Ohm Meters) at 80° F		Rm by SWSCO MC / Rm by SWSCO F T	Resistivity of Mud Filtrate SWSCO Filtrate Tube		Resistivity of Mud Filtrate, Rmf, corrected to SWSCO Mud Cup values		RmfH-RmfL	RmfH-RmfL / RmfH x 100	RmfH / Rm	RmfL / Rm	Resistivity, Rmc, of the Mud Cake by SWSCO Mud Cake tester		RmcH-RmcL	RmcH-RmcL / RmcH x 100	RmcH / Rm	RmcL / Rm	Temperature effect on the resistivity of mud			
		by SWSCO Mud Cup	by SWSCO F Tube		RmfH Ohm Meters	RmfL Ohm Meters	H.P RmfH Ohm Meters	L P RmfL Ohm Meters	Ohm Meters				H P RmcH Ohm Meters	L P RmcL Ohm Meters	Ohm Meters				Rm 80°	Rm 160°	(Rm 80°- Rm160°) / Rm 80° x100	
1	11.0	3.60	3.90	0.923	2.54	2.34	2.33	2.16	+0.17	+7.30 %	0.647	0.600	3.99	4.30	-0.31	-7.75	1.108	1.144				
2	6.0	4.55	4.70	0.968	4.00	3.70	3.87	3.58	+0.29	+8.10 "	0.850	0.787	3.80	3.90	-0.10	-2.63	0.835	0.857				
3	5.0	4.80	5.10	0.941	4.50	4.34	4.23	4.08	+0.15	+3.54 "	0.881	0.850	3.80	3.90	-0.10	-2.63	0.792	0.813				
4	7.0	5.30	5.60	0.946	4.95	4.35	4.55	4.15	+0.40	+8.80 "	0.858	0.783	4.00	4.25	-0.25	-6.25	0.775	0.802				
5	10.0	3.60	4.00	0.900	3.67	3.45	3.30	3.10	+0.20	+6.05 "	0.917	0.861	3.50	3.725	-0.225	-6.42	0.972	1.033				
6	5.0	4.33	4.60	0.941	4.90	4.75	4.61	4.47	+0.14	+3.05 "	1.065	1.032	4.05	3.70	+0.350	+9.75	0.935	0.854				
7	10.0	2.74	3.00	0.913	2.44	2.34	2.23	2.13	+0.10	+4.50 "	0.814	0.777	3.40	3.80	-0.40	-11.75	1.241	1.387				
8	4.0	1.75	2.30	0.716	2.34	2.05	1.78	1.56	+0.22	+12.35 "	1.017	0.891	2.75	2.60	+0.15	+5.45	1.571	1.486				
9	10.5	2.35	2.65	0.886	2.60	2.45	2.30	2.17	+0.13	+5.65 "	0.979	0.923	4.10	4.80	-0.70	-17.05	1.745	2.040	2.35	1.20	1.15	49.2 %
10	3.0	5.10	5.40	0.944	6.20	5.70	5.85	5.40	+0.45	+7.70 "	1.470	1.059							5.10	2.60	2.50	49.0 "
11	4.5	3.05	3.30	0.924	3.00	2.80	2.77	2.59	+0.18	+6.50 "	0.908	0.849	3.55	3.70	-0.15	-4.22	1.164	1.213	3.05	1.57	1.48	48.2 "
12	5.5	2.90	3.05	0.950	2.90	2.65	2.75	2.51	+0.24	+8.72 "	0.948	0.865	3.20	3.05	+0.20	+6.25	1.103	1.034	2.90			
13	2.8	4.75	5.07	0.937	5.10	5.00	4.78	4.68	+0.10	+2.10 "	1.006	0.985	4.10	4.35	-0.25	-6.10	0.863	0.916	4.75	2.29	2.46	51.7 "
14	6.0	5.35	5.70	0.938	5.15	4.80	4.83	4.50	+0.33	+7.33 "	0.903	0.841							5.35	2.63	2.72	50.7 "
15	7.0	4.50	4.90	0.918	5.90	5.37	5.42	4.93	+0.49	+9.02 "	1.204	1.095		4.55				1.071	4.50	2.36	2.14	47.6 "
16	3.5	4.79	5.10	0.939	6.10	5.60	5.73	5.26	+0.47	+9.15 "	1.196	1.098	3.70	4.05	-0.35	-9.45	0.772	0.845	4.79	2.30	2.49	52.0 "
17	6.0	5.40	5.70	0.947	5.52	5.40	5.23	5.02	+0.21	+4.03 "	0.968	0.929	4.70				0.870		5.40	2.78	2.62	48.0 "
18	6.5	3.52	3.80	0.921	4.10	3.90	3.78	3.64	+0.14	+3.70 "	1.074	1.034	3.75	4.275	0.525	-14.0	1.065	1.213	3.43	1.76	1.77	50.2 "
19	7.0	3.95	4.30	0.918	3.10	3.00	2.85	2.75	+0.10	+3.52 "	0.722	0.696	4.95	4.85	+0.10	+2.02	1.253	1.228	3.95	1.91	2.04	51.6 "
20	6.0	3.80	4.00	0.950	4.00	3.90	3.80	3.70	+0.10	+2.64 "	1.000	0.974	3.55	4.05	-0.55	-15.50	0.934	1.066	3.71	1.90	1.92	50.5 "
21	4.0	4.45	4.65	0.957	4.50	4.30	4.31	4.11	+0.20	+5.86 "	0.968	0.924	4.08	4.40	-0.32	-7.84	0.917	0.989	4.45	2.14	2.31	51.9 "
22	5.0	4.40	4.52	0.973	4.68	4.46	4.55	4.34	+0.21	+4.61 "	1.034	0.986	4.5	4.25	-0.20	-4.84	0.920	0.966	4.40	2.21	2.19	49.7 "
23	8.0	2.40	2.65	0.906	2.37	2.19	2.15	1.98	+0.17	+7.90 "	0.896	0.825	2.45	2.60	-0.15	-6.12	1.210	1.083	2.4	1.20	1.20	50.3 "

NOTES

1 Ave $\frac{RmfH - RmfL}{RmfH} \times 100 = +6.2\ \%$

2 Ave $\frac{RmcH - RmcL}{RmcH} \times 100 = -5.5\ \%$

3 Ave $\frac{RmfH}{Rm} = 0.969$

4. Ave $\frac{RmfL}{Rm} = 0.870$

5 Ave $\frac{RmcH}{Rm} = 1.042$

6 Ave $\frac{RmcL}{Rm} = 1.1045$

7 Ave. $\frac{Rm\ 80^\circ\ Rm\ 160^\circ}{Rm\ 160^\circ} \times 100 = 50.0\ \%$

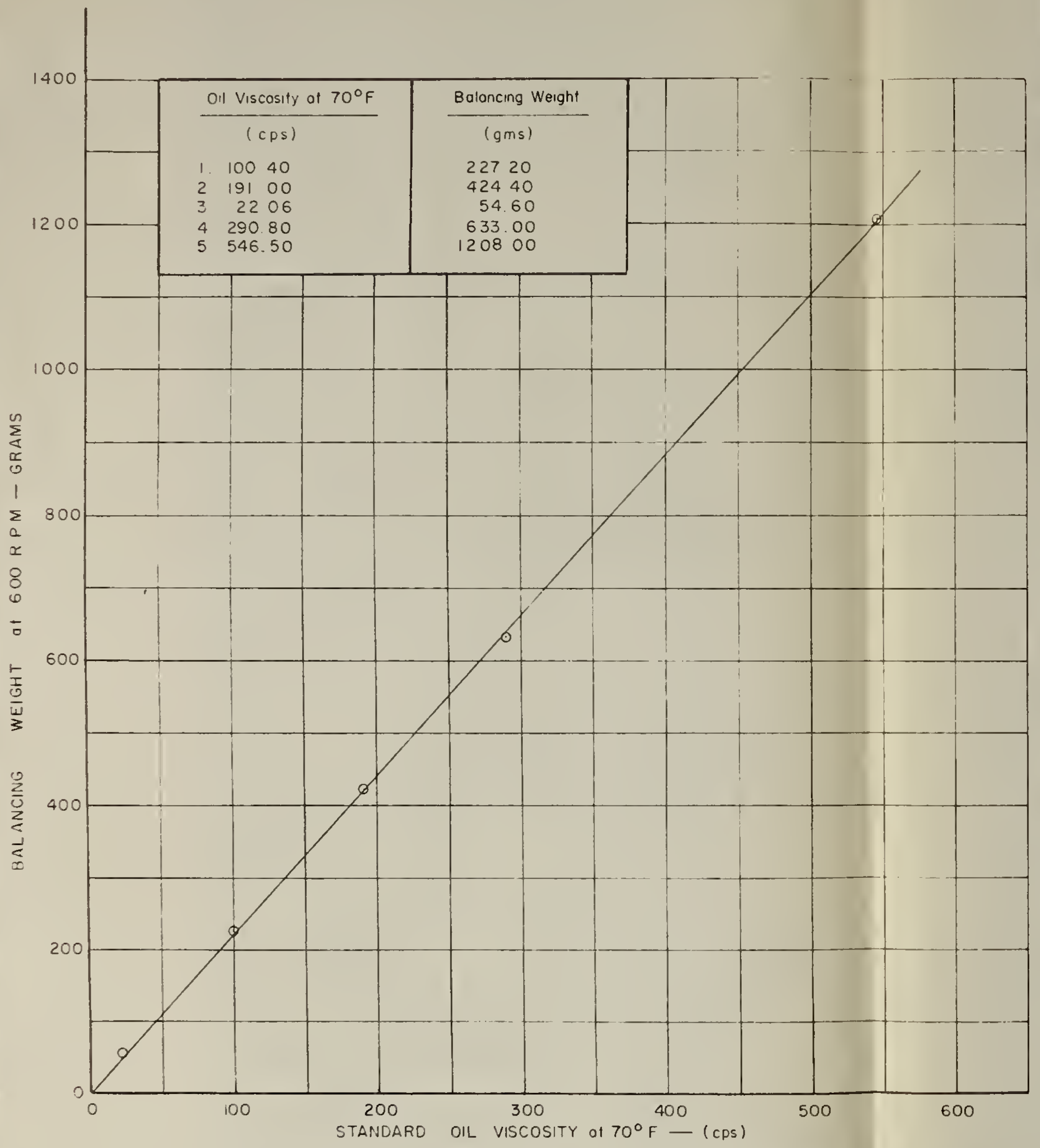
TABLE A-3, VARIATION OF ELECTRICAL RESISTIVITIES AND ELECTRICAL RESISTIVITY RATIOS WITH TEMPERATURE FOR PEMBINA OIL-EMULSION DRILLING FLUIDS

FIELD SAMPLE	RESISTIVITY — OHM METERS at t° F.																	$(Rm)t_1$ / $(Rm)t_2$ VALUES							
	80°	85°	90°	95°	100°	105°	110°	115°	120°	125°	130°	135°	140°	145°	150°	155°	160°	80°/90°	80°/100°	80°/110°	80°/120°	80°/130°	80°/140°	80°/150°	80°/160°
9	2.35	2.28	2.13	2.02	1.92	1.83	1.76	1.68	1.60	1.53	1.46	1.40	1.35	1.31	1.26	1.23	1.20	1.103	1.224	1.335	1.469	1.606	1.741	1.865	1.958
10	5.10	4.62	4.31	4.07	3.88	3.78	3.55	3.40	3.25	3.13	3.01	2.92	2.83	2.75	2.69	2.64	2.59	1.183	1.314	1.437	1.570	1.694	1.802	1.896	1.969
11	3.05		2.73	2.60	2.45	2.36	2.26	2.16	2.06	1.97	1.91	1.82	1.75	1.70	1.65	1.61	1.57	1.117	1.245	1.350	1.481	1.597	1.743	1.848	1.943
13	4.75	4.45	4.20	3.98	3.77	3.58	3.40	3.23	3.07	2.94	2.83	2.70	2.60	2.52	2.44	2.36	2.30	1.131	1.260	1.397	1.547	1.678	1.827	1.947	2.065
14	5.35	5.10	4.85	4.60	4.35	4.15	3.97	3.80	3.65		3.34	3.20	3.06	2.94	2.82	2.70	2.60	1.103	1.230	1.347	1.466	1.602	1.748	1.897	2.058
15	4.50	4.25	4.00	3.80	3.60	3.40	3.25	3.12	3.00	2.90	2.78	2.69	2.60	2.52	2.45	2.40	2.36	1.125	1.250	1.385	1.500	1.619	1.731	1.837	1.908
16	4.79	4.52	4.26		3.85	3.66	3.50	3.35	3.20	3.07	2.93	2.79	2.65	2.53	2.44	2.37	2.30	1.124	1.244	1.369	1.497	1.635	1.807	1.963	2.083
17	5.40		4.78	4.45	4.22	4.00	3.82	3.65	3.50		3.23	3.11	3.01	2.94	2.88	2.84	2.80	1.130	1.280	1.414	1.543	1.672	1.794	1.875	1.929
18	3.50	3.24	3.04	2.92	2.79	2.66	2.52	2.40	2.30	2.22	2.14	2.04	1.96		1.84	1.79	1.75	1.151	1.254	1.390	1.522	1.636	1.786	1.902	2.000
19	3.95		3.40	3.22	3.10	2.92	2.77	2.66	2.56	2.47	2.38		2.20	2.13	2.04	1.96	1.92	1.161	1.274	1.426	1.543	1.660	1.795	1.936	2.057
20	3.80	3.60	3.35	3.12	2.97	2.85	2.74	2.63	2.52		2.32	2.22	2.14	2.06	2.00		1.92	1.134	1.280	1.387	1.508	1.638	1.776	1.900	1.979
21	4.45	4.17	3.87	3.55	3.35	3.20	3.07		2.82	2.71	2.60	2.51	2.42		2.24	2.18	2.13	1.145	1.253	1.450	1.578	1.711	1.839	1.986	2.089
22	4.40	4.18	3.90	3.67	3.45	3.27	3.13	3.00	2.88	2.77	2.67	2.58	2.48	2.41	2.34		2.20	1.128	1.275	1.406	1.528	1.648	1.774	1.880	2.000
23	2.40	2.25	2.13	2.02	1.92	1.83	1.74	1.66	1.59	1.52	1.47		1.37	1.32	1.27	1.24	1.20	1.127	1.250	1.380	1.509	1.633	1.752	1.890	2.000

TABLE A-4, VARIATION OF THE RESISTIVITY OF SODIUM CHLORIE BRINES WITH TEMPERATURE

(Data from SWSCO log interpretation chorts)

Conc. of $NoCl_2$ Sol'n PPM	RESISTIVITY — OHM METERS at t° F.															
	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°	190°	200°
850	8.60	7.50	6.40	5.60	5.10	4.50	4.10	3.70	3.40	3.10	2.85	2.65	2.45	2.25	2.10	2.05
900	7.85	6.90	6.00	5.25	4.70	4.25	3.85	3.50	3.20	2.95	2.70	2.52	2.36	2.23	2.11	2.00
1000	7.00	6.25	5.50	4.90	4.40	3.85	3.50	3.20	2.93	2.68	2.48	2.33	2.18	2.06	1.93	1.80
1100	6.60	5.80	5.10	4.50	3.95	3.55	3.15	2.90	2.65	2.47	2.30	2.15	2.00	1.87	1.75	1.65
1200	6.00	5.40	4.80	4.25	3.65	3.20	2.90	2.65	2.45	2.25	2.07	1.92	1.81	1.72	1.64	1.57
1500	4.90	4.30	3.70	3.30	2.95	2.65	2.40	2.20	2.02	1.85	1.72	1.61	1.51	1.44	1.38	1.33
2000	3.65	3.22	2.85	2.50	2.25	2.00	1.85	1.70	1.53	1.41	1.30	1.22	1.15	1.08	1.02	0.97



	Oil Viscosity at 70°F (cps)	Balancing Weight (gms)
1.	100 40	227 20
2	191 00	424 40
3	22 06	54.60
4	290.80	633.00
5	546.50	1208 00

FIG A-1, CALIBRATION CURVE FOR FANN VISCOSIMETER (Laboratory Model 31 , Serial No. 340)

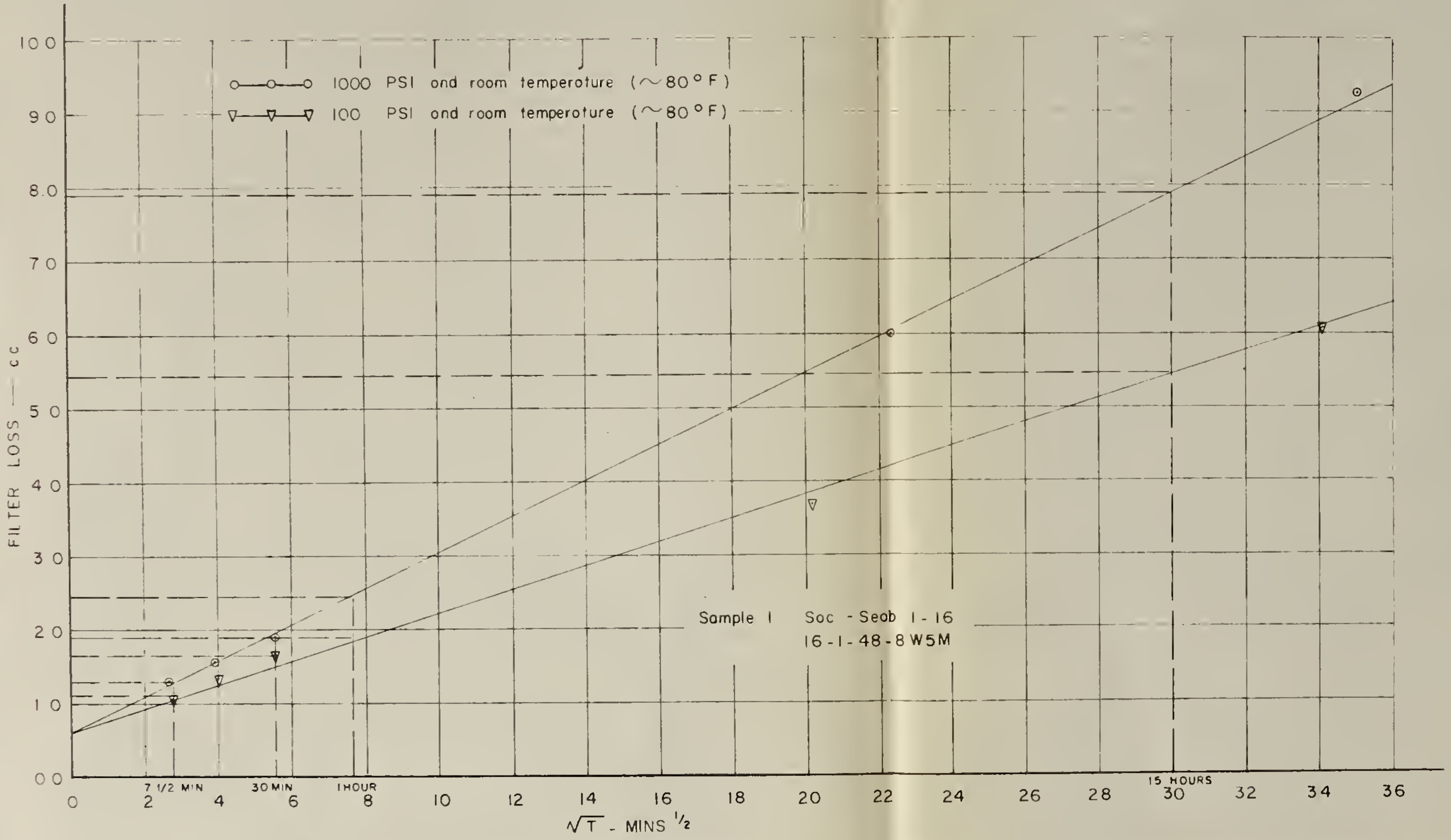


FIG A-2, FILTER-LOSS BEHAVIOR OF A PEMBINA OIL-EMULSION DRILLING FLUID AT TWO LEVELS OF PRESSURE AND ROOM TEMPERATURE (~80° F)

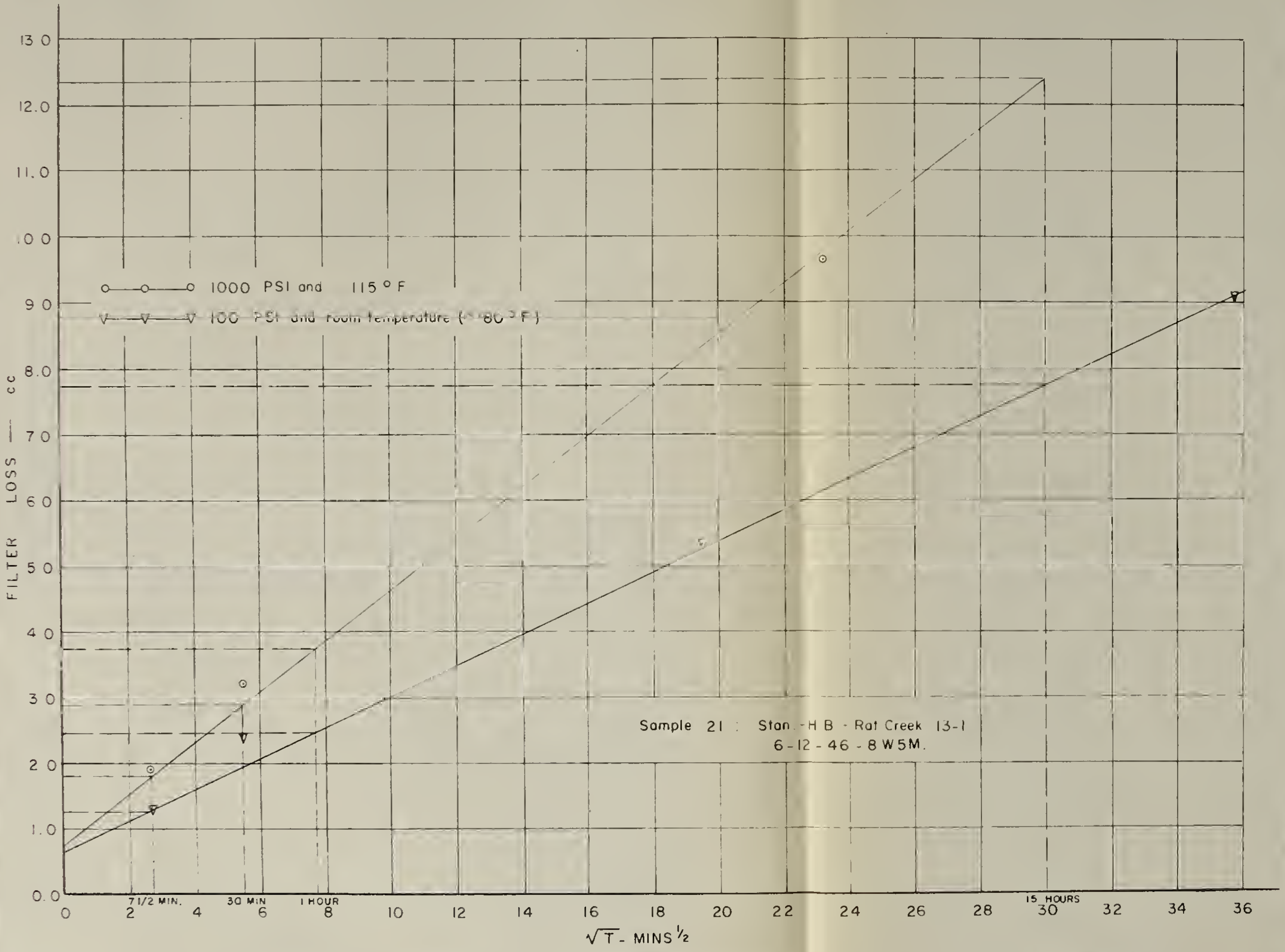


FIG A-3, FILTER LOSS BEHAVIOR OF A PEMBINA OIL-EMULSION DRILLING FLUID AT TWO LEVELS OF PRESSURE AND TEMPERATURE

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